5. Estimates of Direct Damage

5.1 Introduction

The analysis of seismic vulnerability of lifeline systems and the economic impact of disruption is based on an assessment of three factors:

- Seismic hazard,
- Lifeline inventory, and
- Vulnerability functions.

In this investigation these factors are used to quantify vulnerability and impact of disruption in terms of (1) direct damage and (2) economic losses resulting from direct damage and loss of function of damaged facilities. Estimates of direct damage to lifelines, expressed in terms of percent replacement value and dollar loss, are discussed in this chapter. Indirect economic losses are discussed in Chapter 6.

Direct damage is defined as damage resulting directly from ground shaking or other collateral loss causes such as liquefaction. For each facility, it is expressed in terms of cost of repair divided by replacement cost and varies from 0 to 1.0 (0% to 100%). In this project it is estimated using (1) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), (2) inventory data specifying the location and type of facilities affected (from Chapter 2), and (3) vulnerability functions that relate seismic intensity and site conditions to expected damage (from Appendix B).

5.2 General Analytical Approach for Estimating Direct Damage

The earthquake survival of lifelines depends on their seismic performance characteristics. As described in Chapter 3 and summarized in Appendix B, the seismic performance of lifeline components has been characterized in this study using data developed from the database of expert opinion elicited in the ATC-13 project (ATC, 1985). This expert opinion was based in part on observations of lifeline components performance in previous earthquakes as well as estimates of expected performance based on knowledge of seismic design procedures and criteria. Thus, component vulnerability data for this study is essentially empirically based, rather than resulting from detailed analyses of each lifeline component.

The analysis approach to estimate direct damage considers both damage resulting from ground shaking as well as damage resulting from liquefaction. Damage due to other collateral loss causes, such as landslide and fire following earthquake, are not included because of the unavailability of inventory information and the lack of available models for estimating these losses nationwide.

The analysis approach for computing direct damage due to ground shaking proceeded as follows. For each earthquake scenario, MMI levels were assigned to each 25-km grid cell in the affected region, using the Everden MMI model, assigned magnitude, and assigned fault rupture location (from Chapter 4). Damage states were then estimated for each affected lifeline component (node or link) in each grid cell, using the motion-damage curves provided in Appendix B. As described in the following sections, the procedure for utilizing the motion-damage curves varied slightly by facility type, depending on whether the lifeline was a site specific facility, or a regional transmission (extended) network.

Damage due to liquefaction was estimated using a two-step method, also taken from ATC-13 (ATC, 1985). First, the probability of ground failure in each grid cell was calculated on the basis of the soil condition and associated liquefaction probability assessments provided in Table 8.4 of the ATC-13 report (p. 230). Only one soil unit (as defined by Everden) was assumed to be liquefiable: Unit A, which was assumed to be alluvium with water table less than 3-meters deep. Direct damage due to liquefaction in each Unit A grid cell was then estimated as follows:

$$\mathrm{DMG(PG)} = \mathrm{DMG(S)}\ x\ \mathrm{p(GFI)}\ x\ 5 \quad \text{(for surface facilities)} \qquad (5.1)$$

and

$$DMG(PG) = DMG(S) \times p(GFI) \times 10 \quad \text{(for buried facilities)} \qquad (5.2)$$

where:

DMG(S)	= Mean damage caused by shaking
DMG(PG)	= Mean damage caused by poor ground
p(GFI)	= Probability of a given ground failure intensity, taken directly, noncumulatively, from Table 8.4 (ATC-13) for a given shaking intensity

After damages due to ground shaking and liquefaction were established for each facility in each affected grid cell, the total direct damage for each facility was calculated. As suggested in ATC-13, the total direct damage, DMG(T), was simply the sum of damage due to shaking plus damage due to liquefaction, with the sum always equal to or less than 1.0 (100 %):

$$DMG(T) = DMG(S) + DMG(PG) \qquad (5.3)$$

Cautionary Note Regarding Analysis Approach. In the scenario earthquakes it is assumed that the damage factor is uniquely related to the MMI zone in the manner prescribed in ATC-13 (ATC, 1985). There may be one or more MMI zones within each 25 km grid cell, depending on spatial attenuation. In either case, lifeline damage is assumed to be uniform within each MMI zone. Experts who supplied data to the ATC-13 project may question application of their opinions to cases where lifeline damage does not occur uniformly within a grid cell or MMI zone. In the ATC-13 Questionnaire, on which the damage factors and loss of function statistics are based, the damage factor is defined as damage due to ground shaking only (see ATC-13, p. 175). This approach probably led ATC-13 experts to provide an adequate picture of lifeline damage in many cases. For example, damage to pipelines in southern San Fernando Valley as a result of the 1971 earthquake was primarily due to ground shaking, and was geographically distributed in a way that it is reasonable to speak of average damage within a given MMI zone. Damage to pipelines in northern San Fernando Valley was more closely spaced and more severe due to ground rupture and to other significant ground distortions associated with nearby fault movement; at least some experts who provided opinions probably considered the fact that higher MMI is associated with such effects and incorporated it in their response despite instructions to consider only ground shaking. In this case, also, it is reasonable to speak of average damage. Thus, damage due to ground distortion can, at least in some cases, also be presented as uniform or average throughout a given MMI zone. Damage statistics prepared in this way are best applied in situations where not only the hazard (ground shaking and ground distortions) but also the structures of interest (pipelines, highway bridges, electrical substations) are distributed somewhat uniformly. It is significant that most of the pipeline damage statistics from San Fernando and from other earthquakes are derived from distribution and transmission networks, which are relatively dense within the MMI zones considered. The conditions that shaped ATC-13 expert opinion are most nearly approximated in such cases (for example, a dense network of transmission and distribution pipelines); it is reasonable to use ATC-13 damage factors for these situations.

However, to the extent that structures occur sparsely in a grid cell or MMI zone, conditions differ from those on which many expert opinions are based. This is because fewer lifeline components will be damaged at all if there are fewer components to coincide with damaging ground conditions. In the extreme case of a single lifeline structure in a 25-km grid cell, it may be misleading to apply statistics derived from regions with a dense array of structures. In at least some regions of the scenario earthquakes, there appear to be only a few lifeline components passing through the MMI zones or 25-km grid cells. In instances where trunk and transmission lines are sparse in a MMI zone or grid cell, application of ATC-13 statistics may be misleading because structure and hazard coincide much less frequently than is assumed. This possibility introduces an additional type of uncertainty that affects the average damage factors used in this study.

The foregoing discussion is based on intuition, not on rigorous analytical modeling. However, if this discussion is valid, the effect of applying

ATC-13 statistics in this study may result in overestimates of damage.

5.3 Direct Damage Estimates for Site-Specific Lifelines

Direct damage to site-specific lifelines, i.e., lifelines that consist of individual sited or point facilities (e.g., hospitals), were estimated using the methodology specified above. For airports, ports and harbors, medical care facilities (hospitals), and broadcast stations, the inventory data summarized in Chapter 2 were used to define the number and distribution of facilities. For fire and police stations, locations were assumed to be lumped at the center of the Standard Metropolitan Statistical Areas, and number of facilities affected were estimated by proxy, assuming the previously established relationships between population and number of facilities.

For summary and comparative purposes, four damage states are considered in this study:

- Light damage (1-10% replacement value);
- Moderate damage (10-30% replacement value);
- Heavy damage (30-60% replacement value); and
- Major to destroyed (60-100% replacement value).

The total number of affected facilities and the percentage of facilities in each damage state are summarized for each scenario earthquake in Tables 5-1 through 5-6. Following is a discussion of the direct damage impact on each site-specific lifeline considered.

5.3.1 Airports

Direct damage summaries for civil and general aviation airports for the various scenario earthquakes (Tables 5-1a and 5-1b) indicate that damage to terminals is expected to be particularly high in the magnitude-8.0 New Madrid and Puget Sound earthquake scenarios. For example, for the New Madrid magnitude-8.0 event, 13% of the airports in Arkansas (23 in total), 6% of the airports in Missouri (25 in total), and 2% in Tennessee (4 in total) would sustain major to destructive damage (60 to 100%) (Table 5-1a). The Puget Sound magnitude-7.5 scenario event would seriously affect an even larger number of airport terminals, with 12% or approximately 43 airports expected to sustain damage in this same range (60 to 100%). In the case of the Cape Ann and Charleston events, direct damage to terminals is also significant. Direct damage to runways (Table 5-1b), on the other hand, is relatively low for most scenario events; if damage does occur, it is usually less than 30%.

The reason for the relatively high impact on airports in the Puget Sound event is assumed to be due to the high concentration of airports near the source zone and poor ground, i.e., liquefiable sites. For the New Madrid event, the cause appears to be due to a combination of poor ground, low ground-motion attenuation with distance, and lack of seismically resistant design construction features.

5.3.2 Ports and Harbors

Since ports and harbors are located in the coastal regions, only those scenario earthquakes affecting these regions will negatively impact this facility type. As indicated in Table 5-2, the most severe damages to ports and harbors are expected for the Charleston and Puget Sound events. For example, one hundred percent, or 20 ports and harbors, in South Carolina can be expected to sustain heavy damage (30 to 60%), and 73%, or approximately 22 such facilities would be similarly affected in Georgia. In Washington, 14% of the ports (approximately 11) would be similarly affected. Numerous ports and harbors in these states would also sustain moderate damage (10 to 30%), as would approximately 22 such facilities in California for the Hayward magnitude-7.5 event. The primary cause of such damage, of course, is poor ground.

5.3.3 Medical Care Facilities

Direct damage summaries for medical care facilities (hospitals) for the various scenario earthquakes (Table 5-3) suggest that damage to this facility type will be relatively high for the Puget Sound, Charleston, New Madrid, Fort Tejon, and Hayward scenario events. For example, damage data for the Puget Sound and Charleston events indicate that 15% of the hospitals in Washington (15 in total) and 13% of

Table 5-1a Damage Percent for Air Transportation Terminals for Each Scenario Earthquake (Percent of Airports in State)

NEW MADRID (M=8.0)

Total Number	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	11%	5%	17%	18%	26%	64%
Moderate 10-30 %	< 1%	0%	21%	13%	3%	19%
Heavy 30-60 %	0%	0%	5%	0%	0%	0%
Major to Destructive 60-100 %	0%	6%	13%	2%	0%	0%

CHARLESTON (M=7.5)

Total Number	South Carolina 147	North Carolina 309	Georgia 343
Light Damage 1-10 %	33%	24%	28%
Moderate 10-30 %	20%	1%	1%
Heavy 30-60 %	0%	0%	0%
Major to Destructive 60-100 %	4%	0%	2%

CAPE ANN (M=7.0)

Total Number	Massachusetts 149	Connecticut 115	Delaware 37	Rhode Island 55	New Hampshire 63
Light Damage 1-10 %	77%	57%	65%	55%	56%
Moderate 10-30 %	< 1%	0%	0%	0%	0%
Heavy 30-60 %	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	4%	0%	0%	0%	0%

WASATCH FRONT (M=7.5)

Total Number	Utah 107
Light Damage 1-10 %	15%
Moderate 10-30 %	23%
Heavy 30-60 %	0%
Major to Destructive 60-100 %	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)
Total Number	California 869	California 869	Washington 364
Light Damage 1-10 %	9%	12%	15%
Moderate 10-30 %	2%	14%	6%
Heavy 30-60 %	0%	< 1%	6%
Major to Destructive 60-100 %	0%	0%	12%

NEW MADRID (M=7.0)

Total Number	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	< 1%	< 1%	31%	19%	7%	32%
Moderate 10-30 %	0%	2%	12%	< 1%	0%	0%
Heavy 30-60 %	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	3%	1%	2%	0%	0%

Table 5-1b Damage Percent for Air Transportation Runways for Each Scenario Earthquake (Percent of Airports in State)

	NEW MADRID (M=8.0)						CHARLESTON (M=7.5)		
Total Number	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193	South Carolina 147	North Carolina 309	Georgia 343
Light Damage 1-10 %	< 1%	< 1%	20%	3%	< 1%	17%	2%	1%	1%
Moderate 10-30 %	0%	5%	15%	< 1%	0%	0%	3%	0%	2%
Heavy 30-60 %	0%	1%	0%	2%	0%	0%	1%	0%	0%
Major to Destructive 60-100 %	0%	6%	0%	0%	0%	0%	0%	0%	0%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 149	Connecticut 115	Delaware 37	Rhode Island 55	New Hampshire 63	Utah 107
Light Damage 1-10 %	< 1%	0%	0%	0%	0%	5%
Moderate 10-30 %	4%	0%	0%	0%	0%	0%
Heavy 30-60 %	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 869	California 869	Washington 364	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	4%	7%	6%	0%	2%	12%	< 1%	0%	2%
Moderate 10-30 %	2%	14%	16%	0%	3%	1%	< 2%	0%	0%
Heavy 30-60 %	0%	< 1%	0%	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 5-2 Damage Percent for Ports for Selected Scenario Earthquakes (Percent of Ports in State)

	CHARLESTON (M=7.5)			CAPE ANN (M=7.0)				
Total Number	South Carolina 20	North Carolina 16	Georgia 30	Massachusetts 34	Connecticut 22	Delaware 10	Rhode Island 22	New Hampshire 9
Light Damage 1-10 %	0%	0%	10%	100%	0%	0%	86%	0%
Moderate 10-30 %	0%	0%	0%	0%	0%	0%	0%	0%
Heavy 30-60 %	100%	0%	73%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)
Total Number	California 125	California 125	Washington 77
Light Damage 1-10 %	4%	0%	25%
Moderate 10-30 %	22%	34%	26%
Heavy 30-60 %	0%	0%	14%
Major to Destructive 60-100 %	0%	0%	0%

Table 5-3 Damage Percent for Medical Care Facilities for Each Scenario Earthquake (Percent of Facilities in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 249	Missouri 171	Arkansas 99	Tennessee 167	Kentucky 125	Indiana 102	Mississippi 127	South Carolina 91	North Carolina 161	Georgia 207
Light Damage 1-10 %	22%	6%	16%	18%	20%	7%	62%	30%	15%	32%
Moderate 10-30 %	0%	0%	29%	14%	< 1%	0%	17%	7%	2%	1%
Heavy 30-60 %	0%	0%	3%	0%	0%	0%	0%	10%	0%	0%
Major to Destructive 60-100 %	0%	3%	7%	< 1%	0%	0%	0%	3%	0%	1%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 167	Connecticut 66	Delaware 13	Rhode Island 22	New Hampshire 40	Utah 53
Light Damage 1-10 %	90%	50%	46%	82%	48%	17%
Moderate 10-30 %	0%	0%	0%	0%	0%	51%
Heavy 30-60 %	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	2%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)
Total Number	California 478	California 478	Washington 102
Light Damage 1-10%	12%	16%	7%
Moderate 10-30%	16%	20%	18%
Heavy 30-60 %	9%	10%	5%
Major to Destructive 60-100 %	0%	0%	10%

the hospitals in South Carolina (12 in total) would sustain heavy or major-to-destructive damage (30 to 100%). In the New Madrid magnitude-8.0 event, 10% of the hospitals in Arkansas (10 in total) and 3% of the hospitals in Missouri (5 in total) would sustain similar damage. In California, 10% and 9%, or 48 and 43 hospitals, respectively, would sustain heavy damage (30-to-60%) in the Fort Tejon and Hayward scenarios. It is worth noting that results from a separate study by Applied Technology Council (ATC, 1991) appear to be comparable for the magnitude-7.5 Hayward fault scenario.

As in the case of airports, the reason for severe damage to hospital facilities in the Puget Sound, New Madrid, and Charleston events is assumed to be strongly correlated with poor ground conditions and construction practices.

5.3.4 Police and Fire Stations

As in the case of medical care facilities, direct damage data for police and fire stations (Tables 5-4 and 5-5) suggest that damage to this facility type will be more severe for the New Madrid, Charleston, and Puget Sound events than for the California, Wasatch Front, and Cape Ann events. For example, data for the New Madrid magnitude-8.0 event indicate that 9% of the fire stations and 8% of the police stations in Arkansas would sustain heavy or major-to-destructive damage (30 to 100%). Thirteen and twelve percent, respectively, of fire and police stations in South Carolina would be similarly damaged in the Charleston scenario event, and 15% and 8%, respectively, would be similarly affected by the Puget Sound magnitude-7.5 scenario event.

The reason for severe damage to fire and police stations in the Puget Sound, New Madrid, and Charleston events is assumed to be strongly correlated with poor ground conditions and construction practices.

5.3.5 Broadcast Stations

Direct damage to broadcast stations for the eight scenario earthquakes follows a slightly different pattern than for the other site-specific lifelines. As indicated in Table 5-6, direct damage is relatively high for the magnitude-8 New Madrid, Charleston, and Puget Sound events and slightly less for the Wasatch Front and Fort Tejon events. Data for the New Madrid magnitude-8.0 earthquake scenario indicate that 17% of the broadcast stations in Arkansas (approximately 78 in total) would sustain heavy damage or major-to-destructive damage (30 to 100%). For the Charleston event, 23% or 87 broadcast stations would be similarly affected, and for the Puget Sound event, 14% (122 in total) would be similarly affected. Percentages for the Wasatch Front and Fort Tejon equal approximately 5%, representing 54 damaged broadcast stations in Utah and 77 or fewer in California.

5.4 Direct Damage Estimates for Extended Lifeline Networks

This section presents direct damage estimates for extended network lifelines, such as highways, railroads and other networks at the bulk and/or regional level. The inventory data provided in Chapter 2 were used to define the location of all nodes and links. For all systems except pipelines, direct damage is estimated using the methodology specified above. Results are presented in terms of (1) the same four damage states used for site-specific lifelines, and (2) maps indicating the damaged portions of each extended network for the various scenario earthquakes.

For pipelines, direct damage is estimated (1) using the damage curves specified in Appendix B (in terms of breaks per kilometer), (2) a model that estimates the probability of breaks occurring within given lengths of pipe subjected to given earthquake shaking intensities (Khater, M., et al., 1989), and (3) a special procedure for estimating damage due to liquefaction. Breaks are assumed to occur according to a nonhomogeneous Poisson process. The probability P_f of having at least one break in a line with length L is given by

$$P_f(L, MMI(x)) = 1 - \prod_{k=1}^{N} P_s(l_k, MMI_k) \qquad (5.4)$$

where

$$P_s(l_k, MMI_k) = \exp(-\lambda_k x\, l_k) \quad k=1,\ldots,N \qquad (5.5)$$

in which Π is the multiplier operator; N is the number of grid cells through which the pipeline

Table 5-4 Damage Percent for Fire Stations for Each Scenario Earthquake (Percent of Stations in State)

	NEW MADRID (M=8.0)						CHARLESTON (M=7.5)		
Total Number	Illinois 923	Missouri 41	Arkansas 185	Tennessee 378	Kentucky 285	Mississippi 200	South Carolina 275	North Carolina 570	Georgia 490
Light Damage 1-10 %	4%	2%	15%	18%	6%	14%	18%	2%	14%
Moderate 10-30 %	2%	1%	15%	5%	0%	10%	1%	0%	1%
Heavy 30-60 %	0%	2%	9%	0%	0%	0%	13%	0%	1%
Major to Destructive 60-100 %	0%	< 1%	0%	< 1%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)				
Total Number	California 2230	California 2230	Washington 361	Missouri 410	Arkansas 185	Tennessee 378	Kentucky 285	Mississippi 200
Light Damage 1-10 %	7%	15%	3%	0%	15%	10%	< 1%	5%
Moderate 10-30 %	3%	27%	18%	1%	8%	0%	0%	0%
Heavy 30-60 %	0%	0%	15%	1%	0%	< 1%	0%	0%
Major to Destructive 60-100 %	0%	< 1%	0%	0%	0%	0%	0%	0%

	CAPE ANN (M=7.0)		WASATCH FRONT (M=7.5)
Total Number	Massachusetts 459	Rhode Island 69	Utah 140
Light Damage 1-10%	57%	5%	51%
Moderate 10-30%	0%	0%	11%
Heavy 30-60 %	2%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%

Table 5-5 Damage Percent for Police Stations for Each Scenario Earthquake (Percent of Stations in State)

	NEW MADRID (M=8.0)						CHARLESTON (M=7.5)		
	Illinois	Missouri	Arkansas	Tennessee	Kentucky	Mississippi	South Carolina	North Carolina	Georgia
Total Number	232	102	48	98	74	52	70	132	126
Light Damage 1-10 %	4%	2%	14%	10%	5%	13%	16%	2%	13%
Moderate 10-30 %	2%	1%	10%	5%	0%	9%	1%	0%	1%
Heavy 30-60 %	0%	2%	8%	0%	0%	0%	12%	0%	1%
Major to Destructive 60-100 %	0%	<1%	0%	<1%	0%	0%	0%	0%	0%

	CAPE ANN (M=7.0)		WASATCH FRONT (M=7.5)	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)				
	Massachusetts	Rhode Island	Utah	California	California	Washington	Missouri	Arkansas	Tennessee	Kentucky	Mississippi
Total Number	118	18	34	580	580	94	102	48	98	74	52
Light Damage 1-10 %	26%	5%	22%	6%	14%	3%	0%	14%	9%	<1%	5%
Moderate 10-30 %	0%	0%	10%	3%	8%	16%	1%	7%	0%	0%	0%
Heavy 30-60 %	2%	0%	0%	0%	0%	8%	1%	0%	<1%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	<1%	0%	0%	0%	0%	0%	0%

Table 5-6 Damage Percent for Broadcast Stations for Each Scenario Earthquake (Percent of Stations in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 600	Missouri 524	Arkansas 456	Tennessee 587	Kentucky 474	Indiana 407	Mississippi 416	South Carolina 377	North Carolina 697	Georgia 604
Light Damage 1-10 %	8%	6%	16%	6%	16%	4%	51%	15%	17%	23%
Moderate 10-30 %	< 1%	0%	14%	20%	7%	0%	16%	24%	4%	16%
Heavy 30-60 %	0%	0%	12%	4%	< 1%	0%	12%	5%	1%	1%
Major to Destructive 60-100 %	0%	4%	5%	1%	1%	0%	0%	18%	0%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT M=7.5)
Total Number	Massachusetts 274	Connecticut 155	Delaware 42	Rhode Island 53	New Hampshire 112	Utah 900
Light Damage 1-10 %	38%	50%	74%	70%	40%	10%
Moderate 10-30 %	35%	0%	0%	26%	0%	27%
Heavy 30-60 %	0%	0%	0%	0%	0%	5%
Major to Destructive 60-100 %	1%	0%	0%	0%	0%	0%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 1,538	California 1,538	Washington 872	Illinois 600	Missouri 524	Arkansas 456	Tennessee 587	Kentucky 474	Mississippi 416
Light Damage 1-10 %	4%	16%	2%	0%	1%	12%	13%	6%	15%
Moderate 10-30 %	8%	4%	8%	< 1%	0%	15%	11%	2%	3%
Heavy 30-60 %	1%	4%	5%	0%	1%	4%	< 1%	1%	0%
Major to Destructive 60-100 %	0%	< 1%	9%	0%	2%	0%	1%	0%	0%

Table 5-7 Damage to Railroad System (Length of Roadbed, Km)

Events	Light Damage 1-10%	Moderate 10-30%	Heavy 30-60%	Major to Destructive 60-100%
Cape Ann	0	0	63	0
Charleston	890	85	980	0
Fort Tejon	640	340	825	47
Hayward	988	47	445	140
New Madrid (M=8.0)	3,000	670	1,780	485
New Madrid (M=7.0)	1,198	0	640	0
Puget Sound	340	0	650	0
Wasatch Front	770	300	0	0
Total System Length = 270,611 km				

passes; l_k and MMI_k are the length of the lifeline element and the Modified Mercalli Intensity, respectively, within grid cell k; and λ_k is the mean break rate (taken from Appendix B).

Maps are provided showing sections of pipeline for which the probability of failure exceeds 60% for the various scenario earthquakes. For soil conditions where liquefaction is possible, a break is assumed at each location where the pipeline crosses into a liquefiable zone.

5.4.1 Railroad System

The railroad system is a highly redundant system, and damage to the system due to the selected events was found to be relatively localized to the epicentral area. Direct damage to the railroad system for each scenario event is summarized in Table 5-7, which lists the length (km) of damaged railroad right-of-way within each damage state. The damage estimates are based on damage curves for track/roadbed and exclude damage to related facility types not included in the project inventory--railway terminals, railway bridges and tunnels.

The direct damage data suggest that the magnitude-8 New Madrid, Fort Tejon, and Hayward events would cause the most extensive damage, with 2,265 km, 872 km, and 585 km of roadbed, respectively, sustaining damage in the 30 to 100% range. Damage in the Charleston, Puget Sound, and magnitude-7.0 New Madrid events would also be severe, with 980, 650, and 640 km of roadbed, respectively, sustaining heavy damage (30-to-60 %). Maps showing the distribution of damage to the railroad system for each of the 8 events are provided in Figures 5-1 to 5-8.

5.4.2 Highway System

The highway system is also a highly redundant system, consisting of freeways/highways and bridges. As is in the case of the railroad system, damage to the highway system for each scenario event was found to be localized to the epicentral area. Direct damage to freeways/highways, expressed in terms of km of roadway in the various damage states, are summarized in Table 5-8 and plotted on Figures 5-9 to 5-16 for the eight scenario earthquakes. Bridge damage, expressed in terms of the percent of bridges in each damage state, is summarized in Table 5-9. The roadway and bridge damage data are based, respectively, on damage curves for freeways/highways and for conventional bridges; the estimates exclude damage to tunnels, which are not included in the project inventory. We note also that all bridges are assumed to be conventional bridges because of (1) lack of capacity/size information in the project inventory and (2) the very small percentage of major bridges in the overall national database.

Tables 5-8 and 5-9 indicate that direct damage is not expected to be as severe for freeways/highways as it is for bridges. For

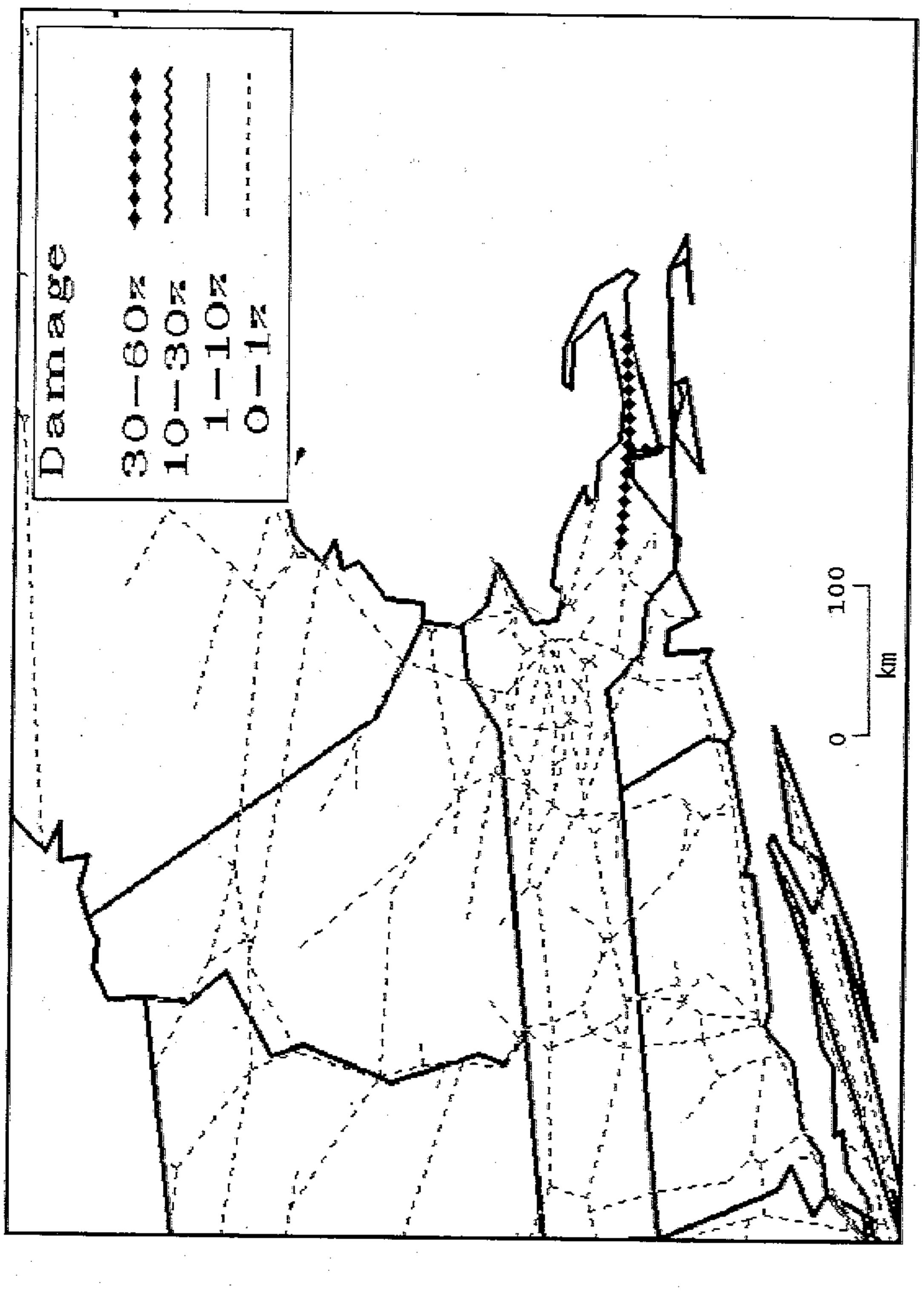

Figure 5-1 *Damage to railroad system following Cape Ann event (M=7.0).*

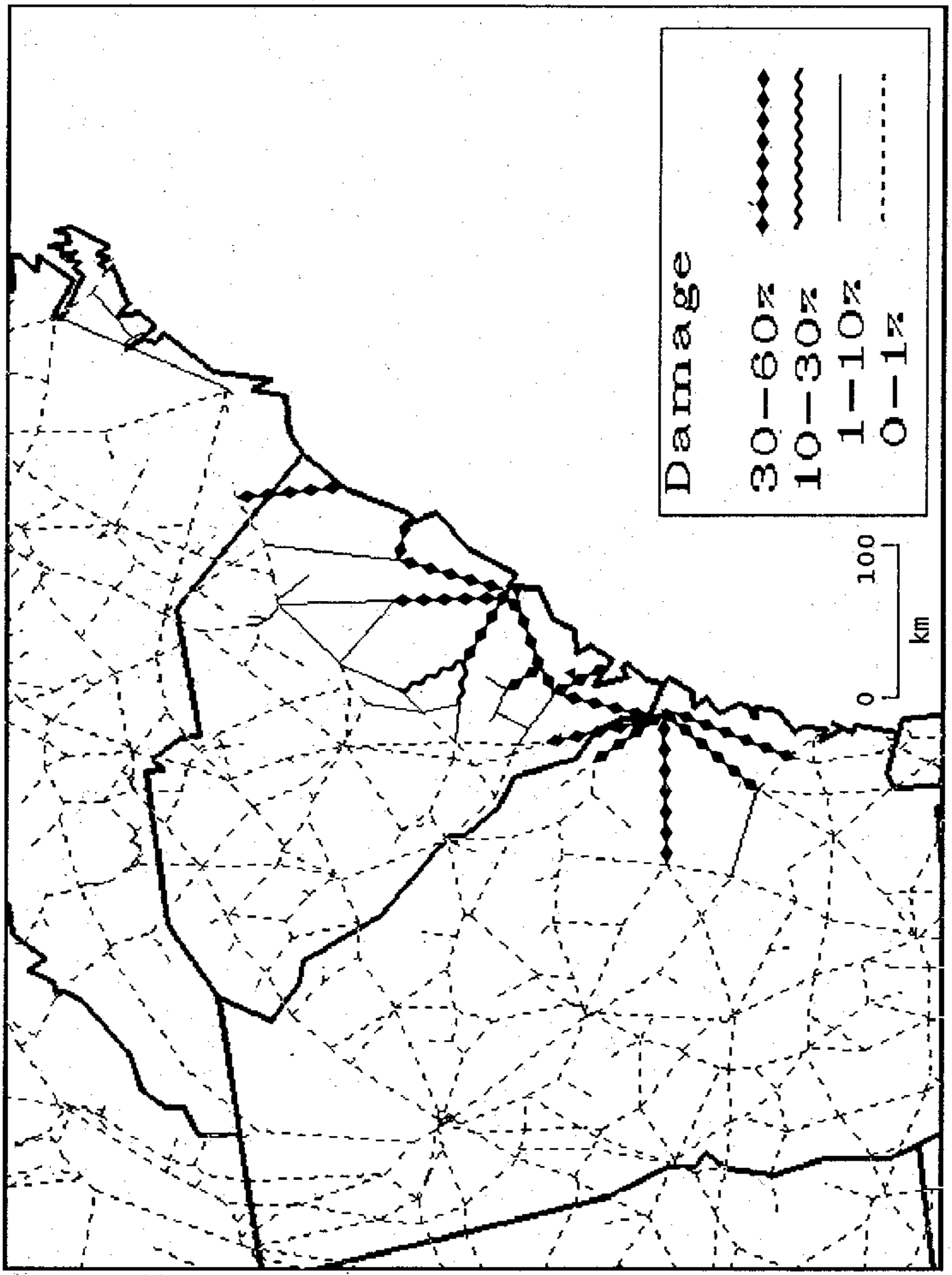

Figure 5-2. *Damage to railroad system following Charleston event (M=7.5).*

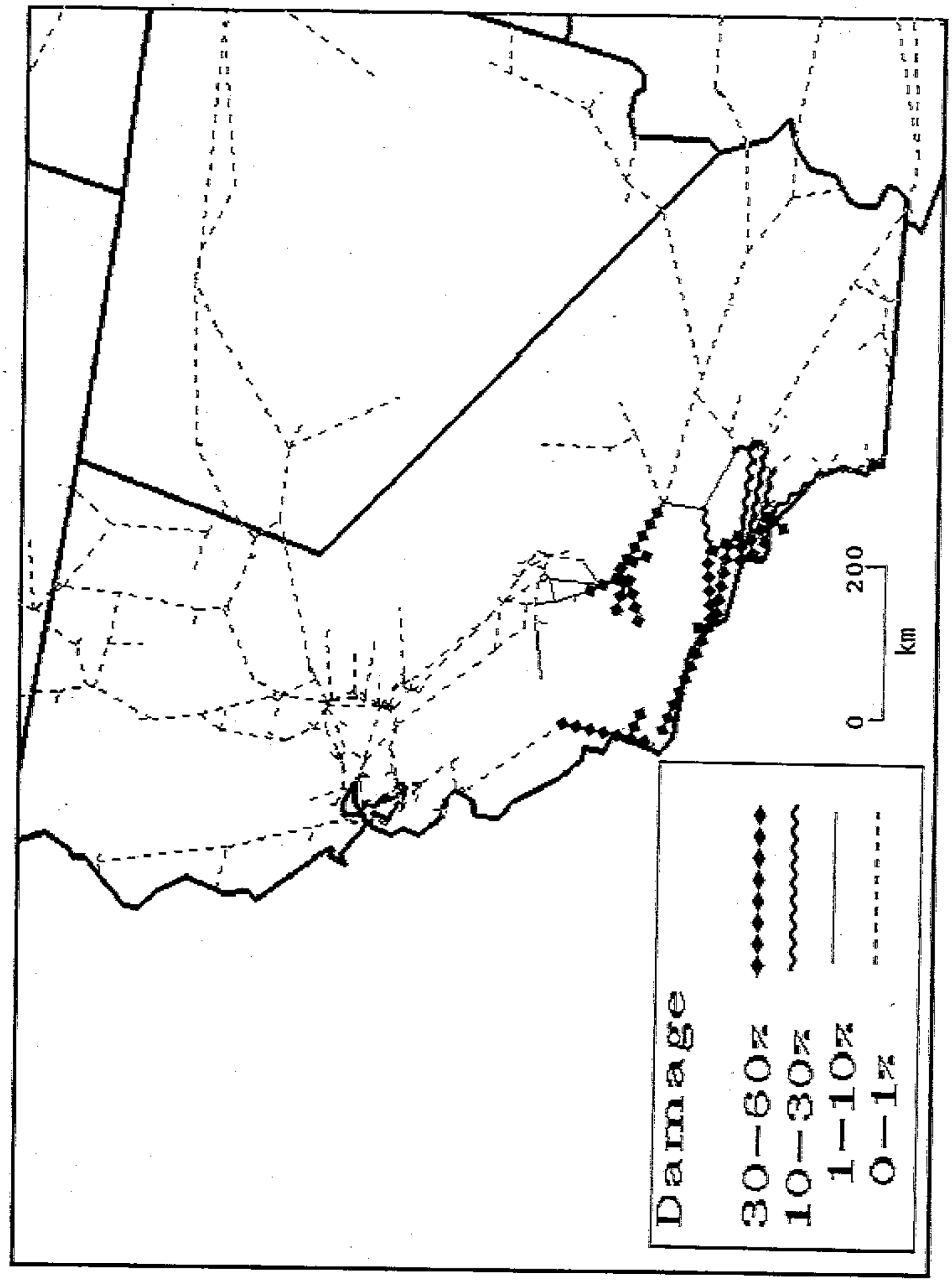

Figure 5-3 *Damage to railroad system following Fort Tejon event (M=8.0).*

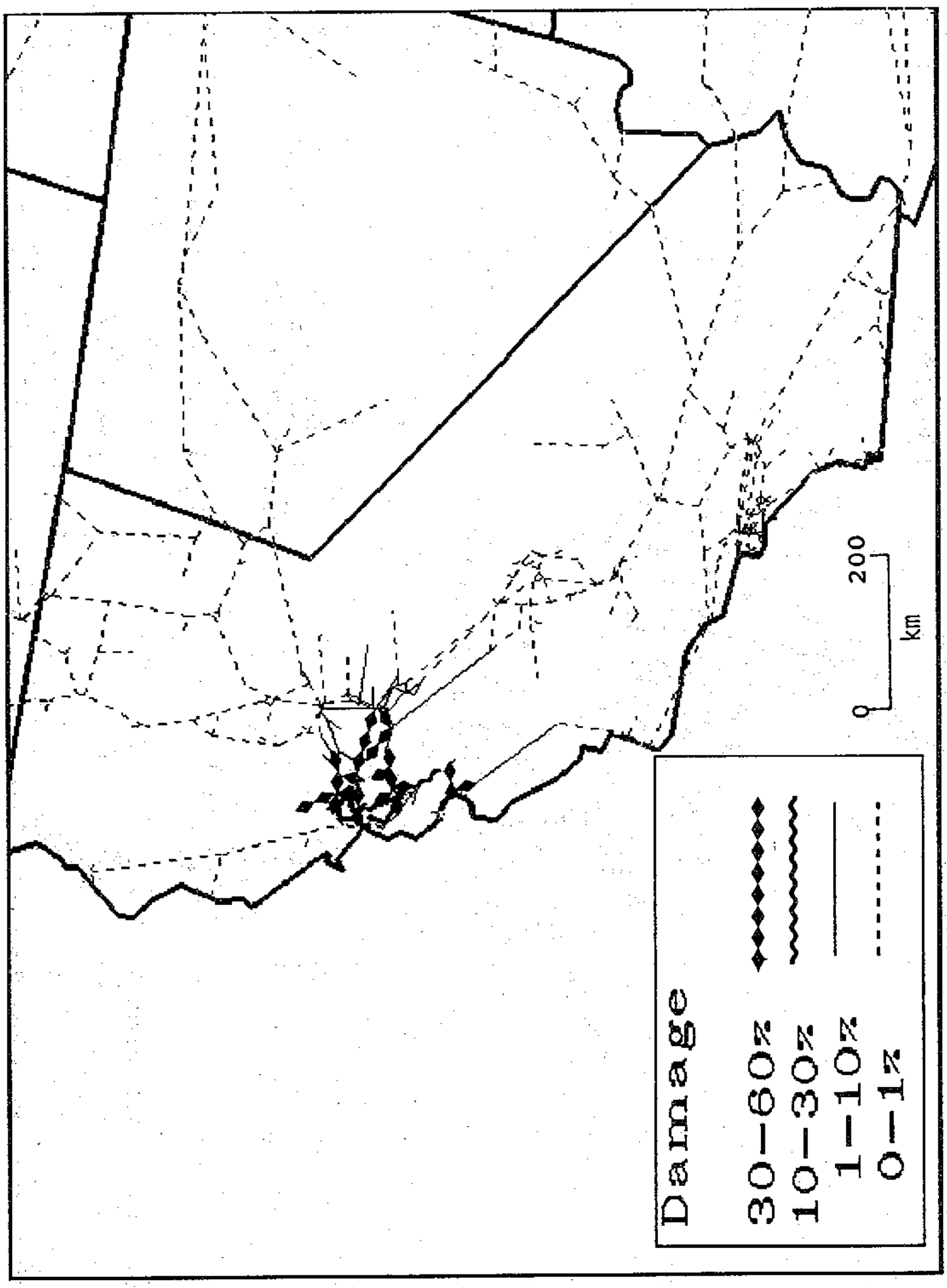

Figure 5-4 *Damage to railroad system following Hayward event (M=7.5).*

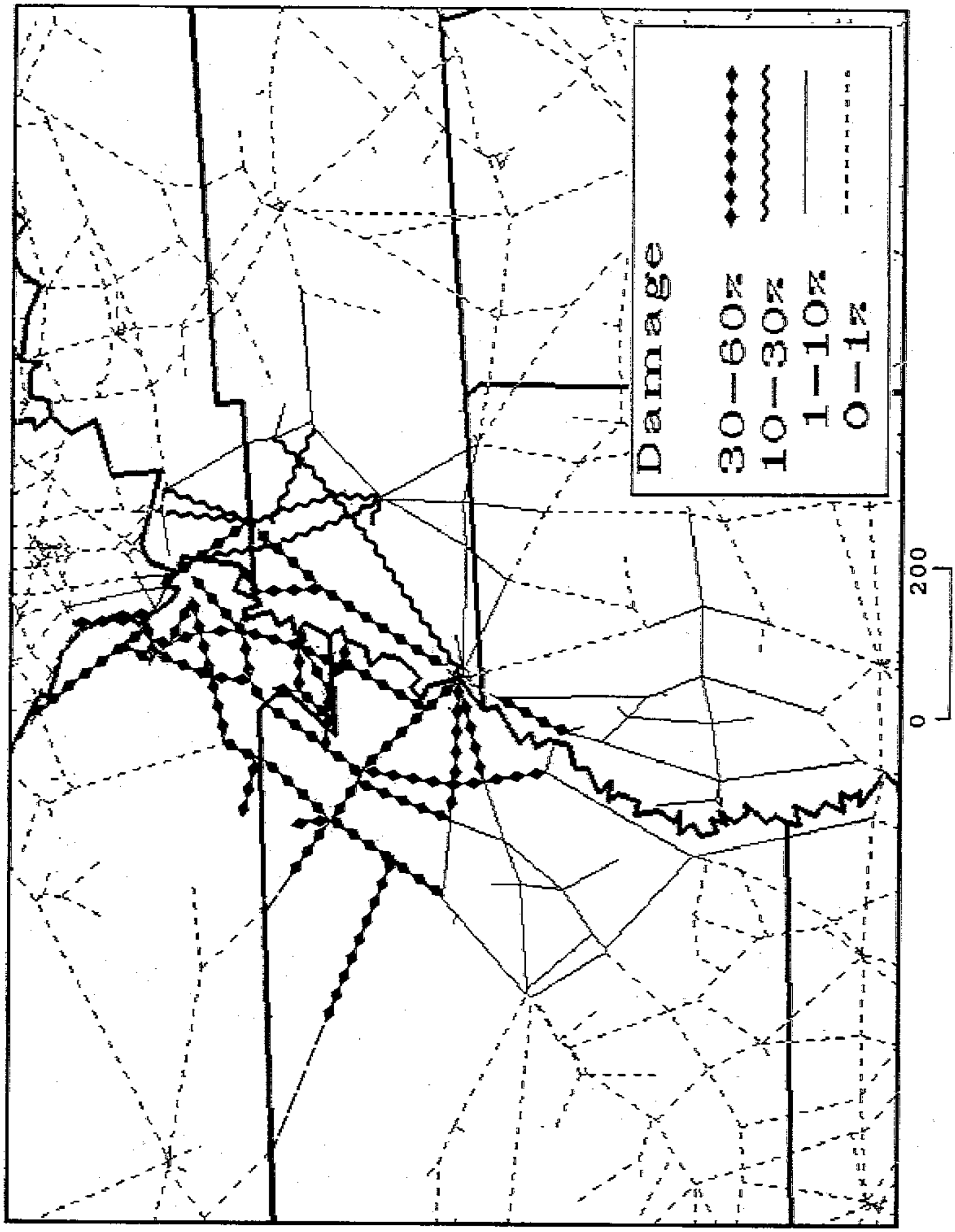

Figure 5-5 Damage to railroad system following New Madrid event (M=8.0).

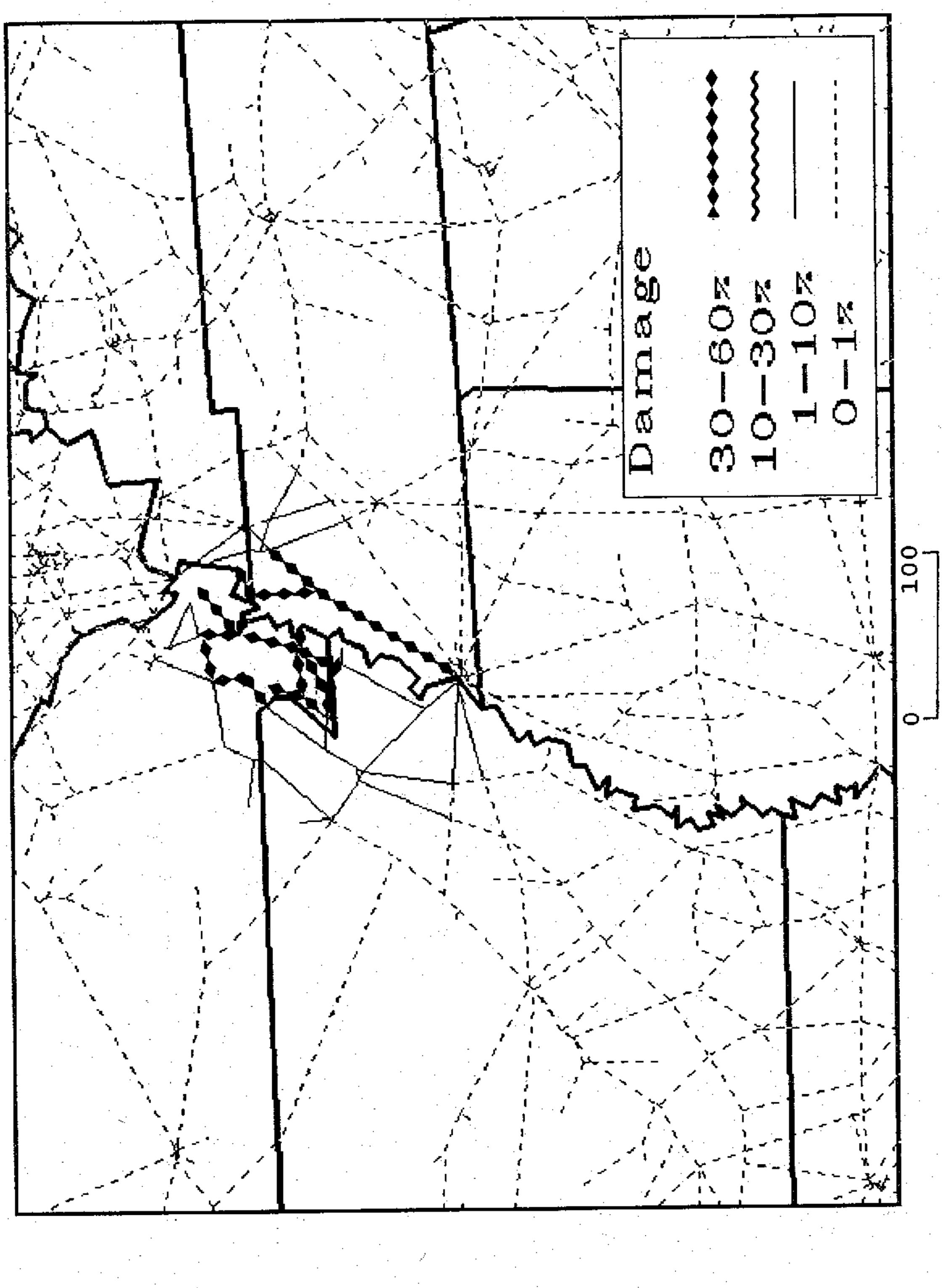

Figure 5-6 Damage to railroad system following New Madrid event (M=7.0).

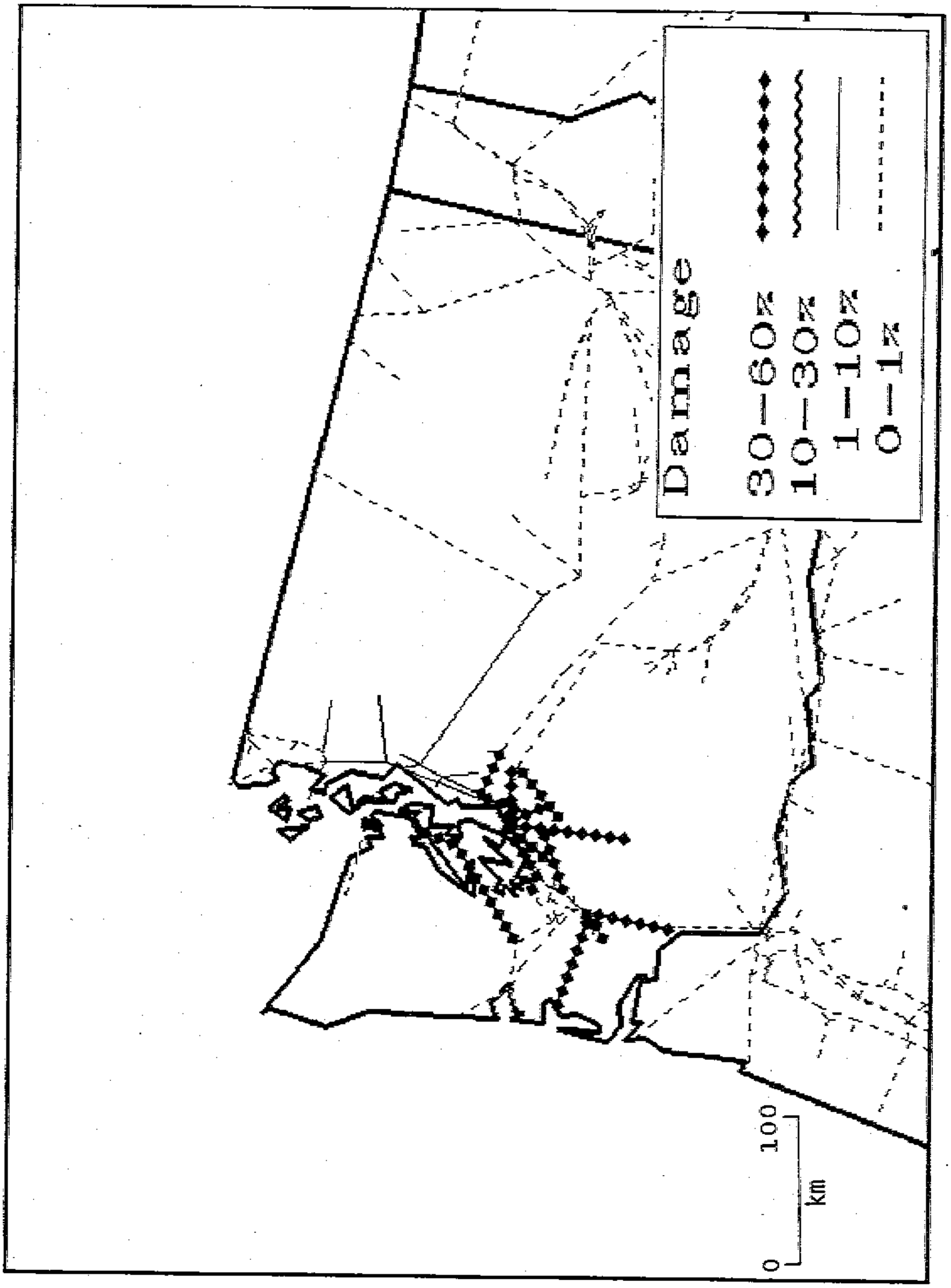

Figure 5-7 Damage to railroad system following Puget Sound event (M=7.5).

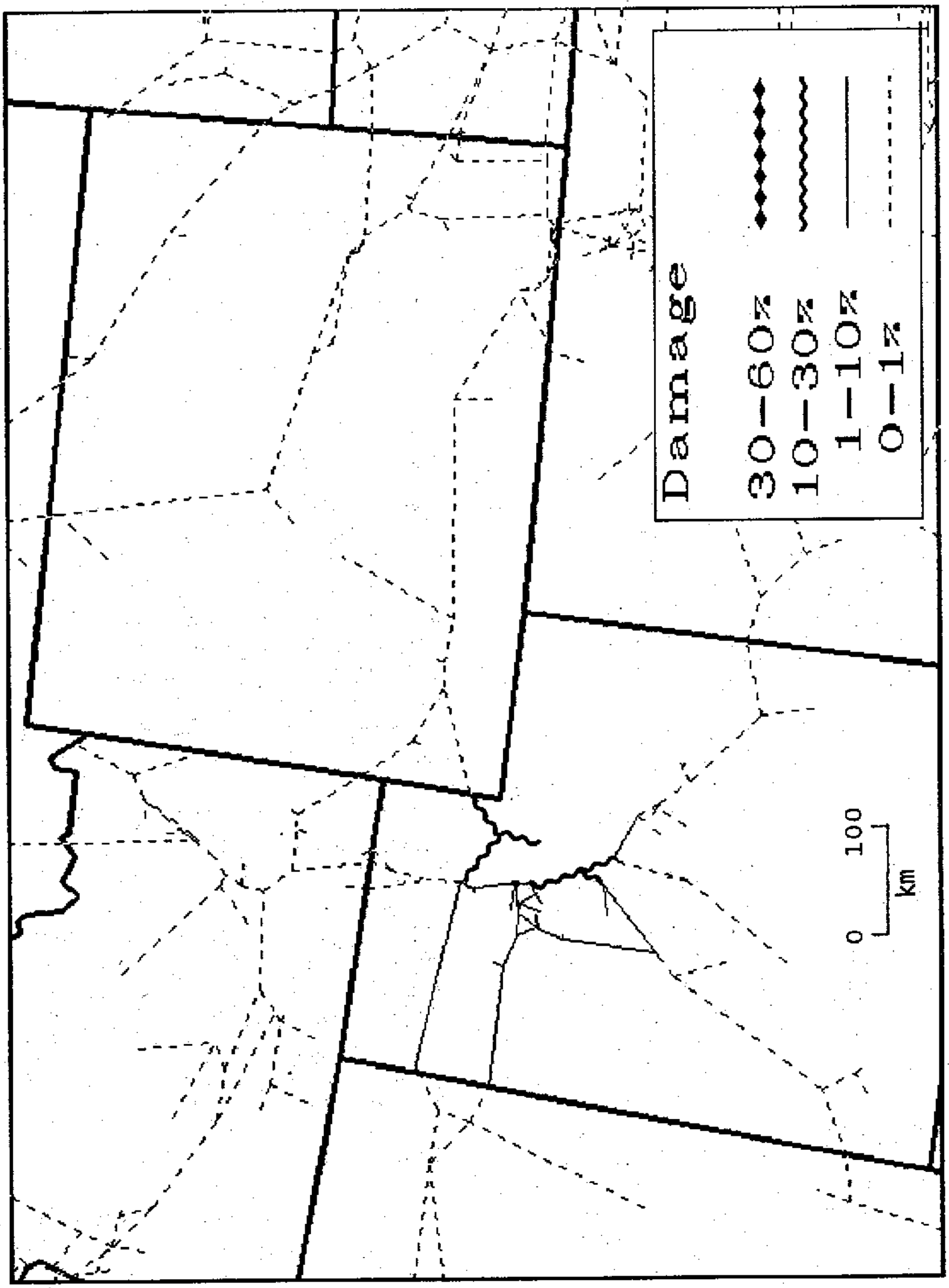

Figure 5-8 Damage to railroad system following Wasatch Front event (M=7.5).

Table 5-8 Damage to Freeway/Highway System (Length of Highway, Km)

Event	*Light Damage 1-10%*	*Moderate 10-30%*	*Heavy 30-60%*	*Major to Destructive 60-100%*
Cape Ann	74	182	0	0
Charleston	2,182	999	0	0
Fort Tejon	2,174	1,557	0	0
Hayward	1,567	476	0	0
New Madrid (M=8.0)	4,967	2,753	0	0
New Madrid (M=7.0)	1,800	720	0	0
Puget Sound	665	769	0	0
Wasatch Front	1,392	0	0	0

Total System Length = 489,892 km

example, direct damage to freeways/highways is not expected to exceed 30% at any location for any scenario earthquake. Data for bridges (Table 5-9), however, suggest that direct damage will range from 30-to-100 % for various locations affected by the Charleston, New Madrid (magnitude-8.0), Puget Sound, and Wasatch Front events. Bridges in Utah appear to be at the greatest risk, with 25 percent of the bridges (approximately 287 bridges) expected to sustain damage in the 30-to-100 % range. Eighteen percent of the bridges in Arkansas (approximately 423), 16 % in Washington (approximately 305), and eleven percent in Tennessee (approximately 407) would sustain similar levels of damage. The difference in expected performance between highways and bridges results from the difference in damage curves for these two structure types.

5.4.3 *Electric System*

Direct damage estimates for the electric system are based on curves for transmission lines and transmission substations and exclude damage to related facility types not included in the project inventory--nuclear and fossil-fuel power plants, and hydroelectric power plants (dams). Damage data for each scenario earthquake are summarized in Tables 5-10 and 5-11, which provide the length of transmissions lines and percent of substations, respectively, in each damage state. Maps provided in Figures 5-17 through 5-24 show plots of damage to transmission lines for the eight scenario earthquakes.

Damage data for transmission lines (Table 5-10 and Figures 5-17 through 5-24) indicate that damage to this facility type is expected to be greatest for the New Madrid (magnitude 8.0) and Fort Tejon events, in which 800 km and 1370 km, respectively, would sustain damage ranging from 10-to-30 %.

Direct damage data for transmission substations, summarized in Table 5-11, indicate that this facility type would be severely impacted in all scenario events. The impacts are most severe in the Puget Sound, magnitude-8.0 New Madrid, Wasatch Front, Charleston, and Hayward events. For these scenario earthquakes, 46 % of the transmission substations in Washington, 39 % in Arkansas, 30 % in South Carolina, 30 % in Utah and 27 % in California would sustain damage in the 30-to-100 % range.

5.4.4 *Water System*

Direct damage to those water transmission systems for which inventory data are available are summarized in Tables 5-12 and 5-13. These estimates are based on damage curves for aqueducts and exclude damage to pumping stations and dams, which are not included in the project inventory. The data indicate that 38 and 20 km of the aqueduct system (Table 5-12), respectively, would sustain moderate to heavy damage (10-to-60 %) in the Fort Tejon and

Table 5-9 Damage Percent for Highway Bridges for Each Scenario Earthquake (Percent of Bridges in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 4,674	Missouri 4,496	Arkansas 2,353	Tennessee 3,698	Kentucky 2,797	Indiana 3,326	Mississippi 3,096	South Carolina 2,134	North Carolina 3,120	Georgia 4,193
Light Damage 1-10 %	10%	6%	16%	8%	16%	2%	56%	15%	9%	17%
Moderate 10-30 %	1%	0%	12%	9%	3%	0%	16%	15%	1%	17%
Heavy 30-60 %	0%	0%	5%	4%	0%	0%	0%	6%	< 1%	< 1%
Major to Destructive 60-100 %	< 1%	0%	13%	7%	3%	0%	8%	1%	< 1%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 2,013	Connecticut 1,878	Delaware 297	Rhode Island 283	New Hampshire 1,020	Utah 1,149
Light Damage 1-10 %	46%	45%	21%	76%	53%	7%
Moderate 10-30 %	37%	0%	0%	15%	1%	11%
Heavy 30-60 %	0%	0%	0%	0%	0%	10%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	15%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)
Total Number	California 7,948	California 7,948	Washington 1,908
Light Damage 1-10 %	4%	22%	8%
Moderate 10-30 %	2%	< 1%	12%
Heavy 30-60 %	0%	0%	3%
Major to Destructive 60-100 %	0%	0%	13%

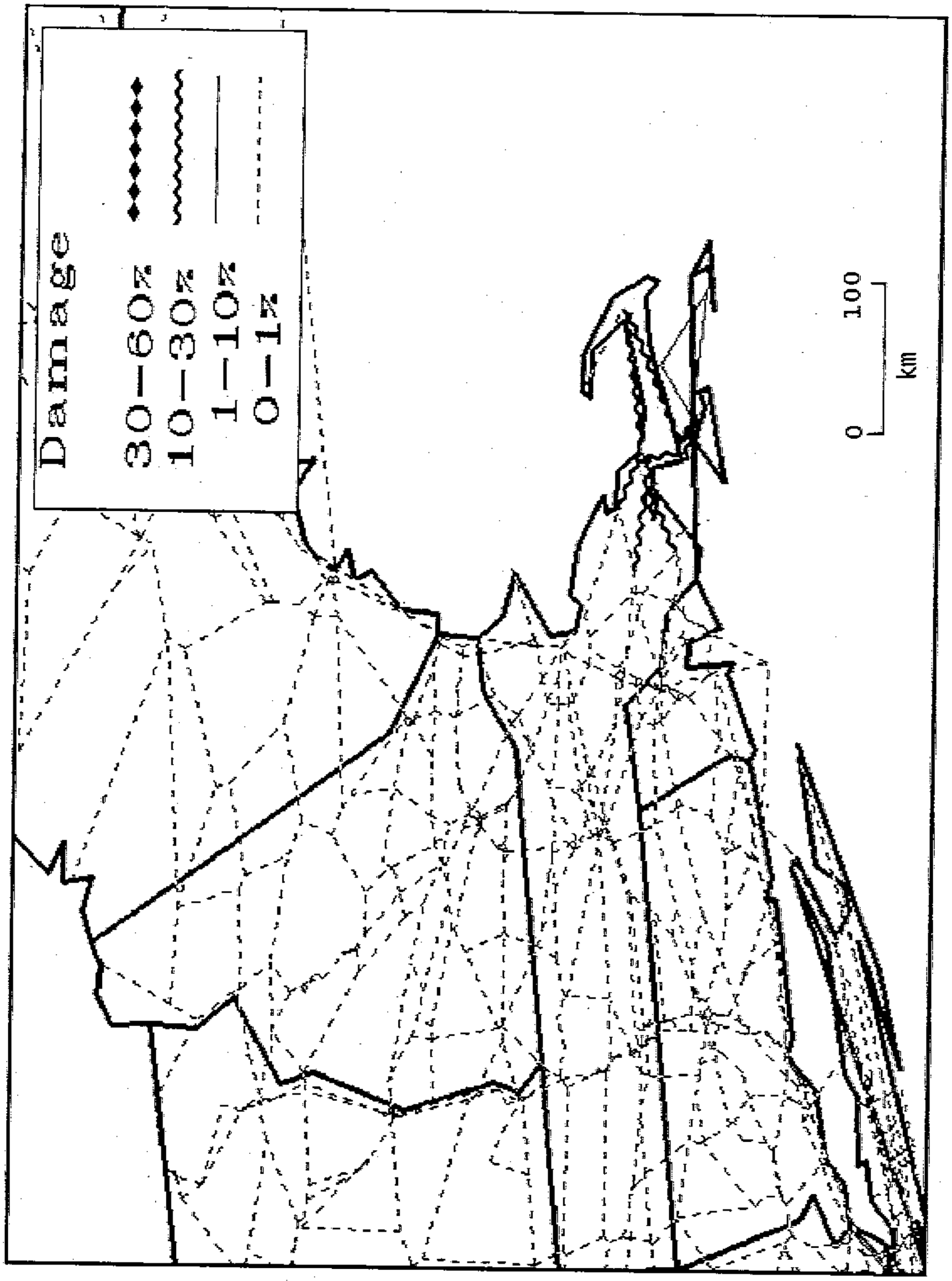

Figure 5-9 *Damage to highways following Cape Ann event (M=7.0).*

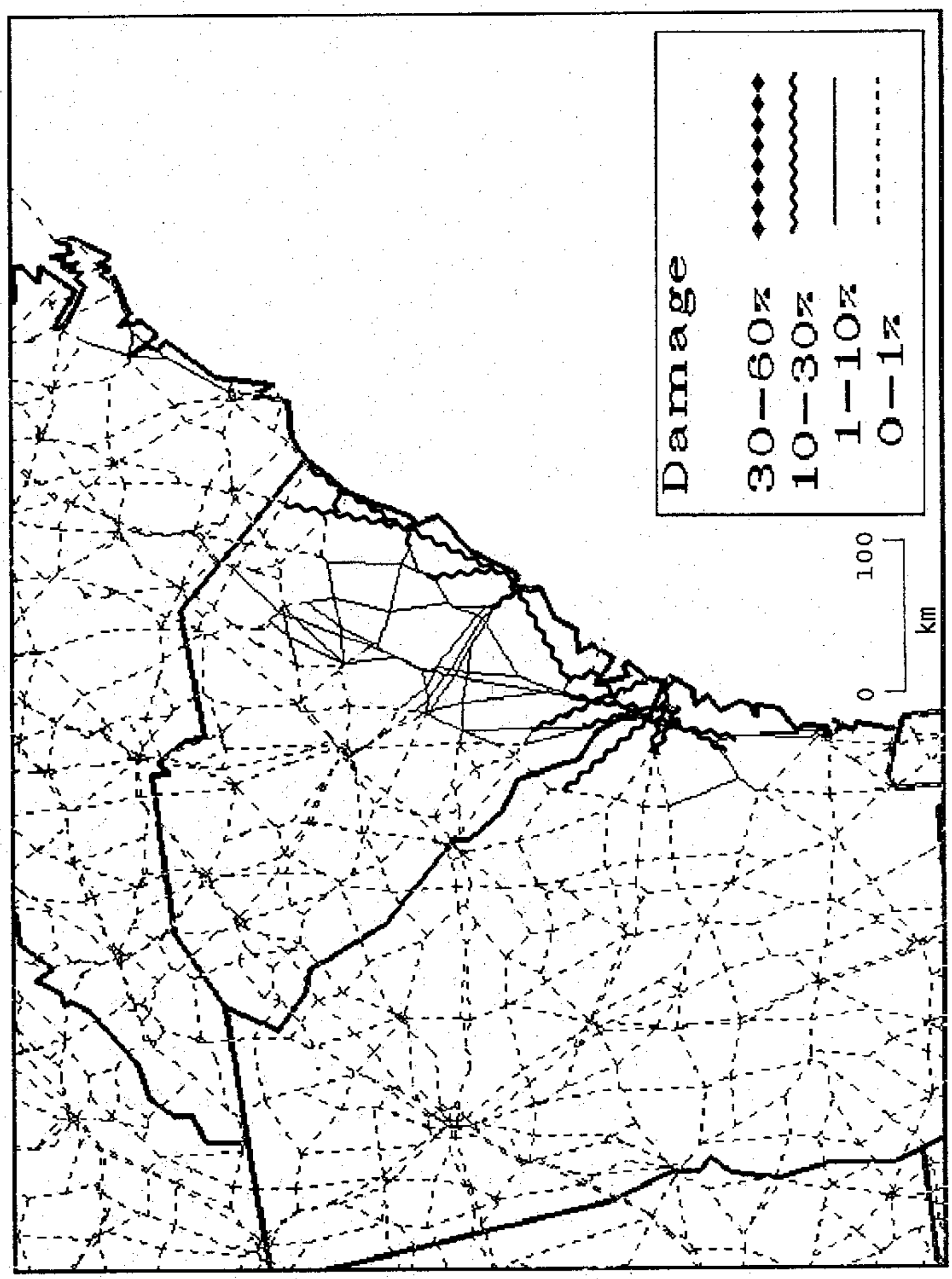

Figure 5-10 *Damage to highways following Charleston event (M=7.5).*

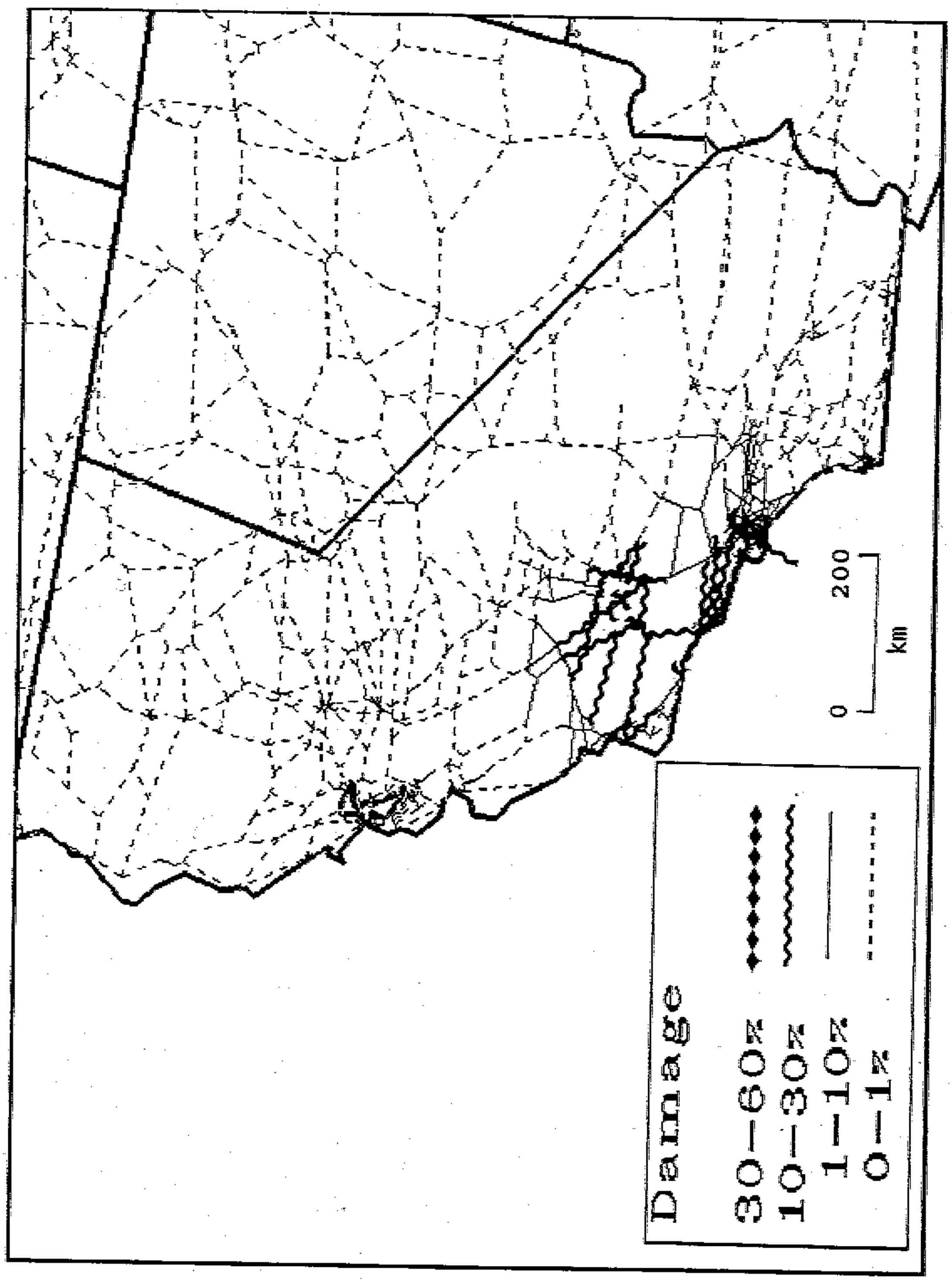

Figure 5-11 *Damage to highways following Fort Tejon event (M=8.0).*

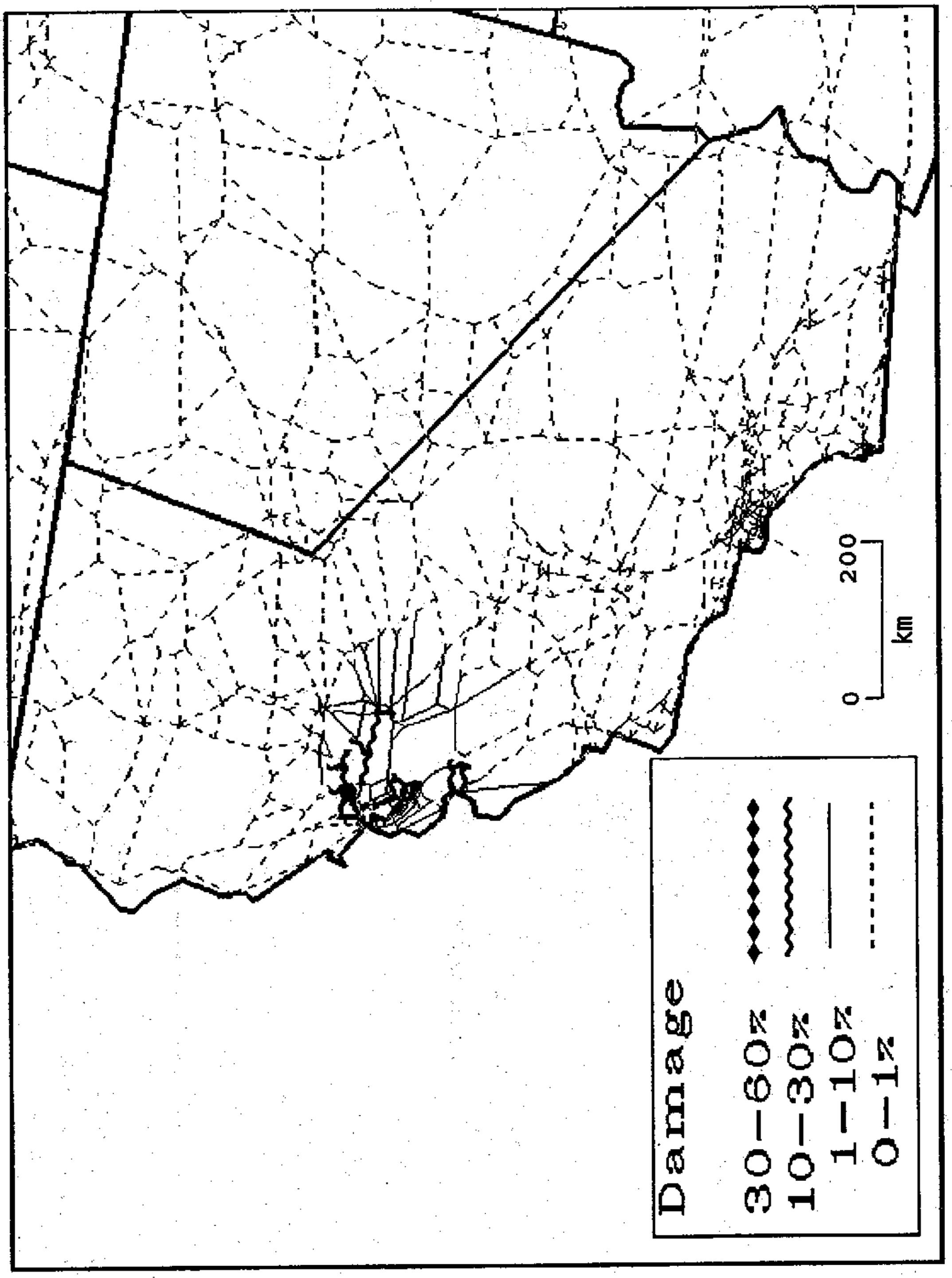

Figure 5-12 Damage to highways following Hayward event (M=7.5).

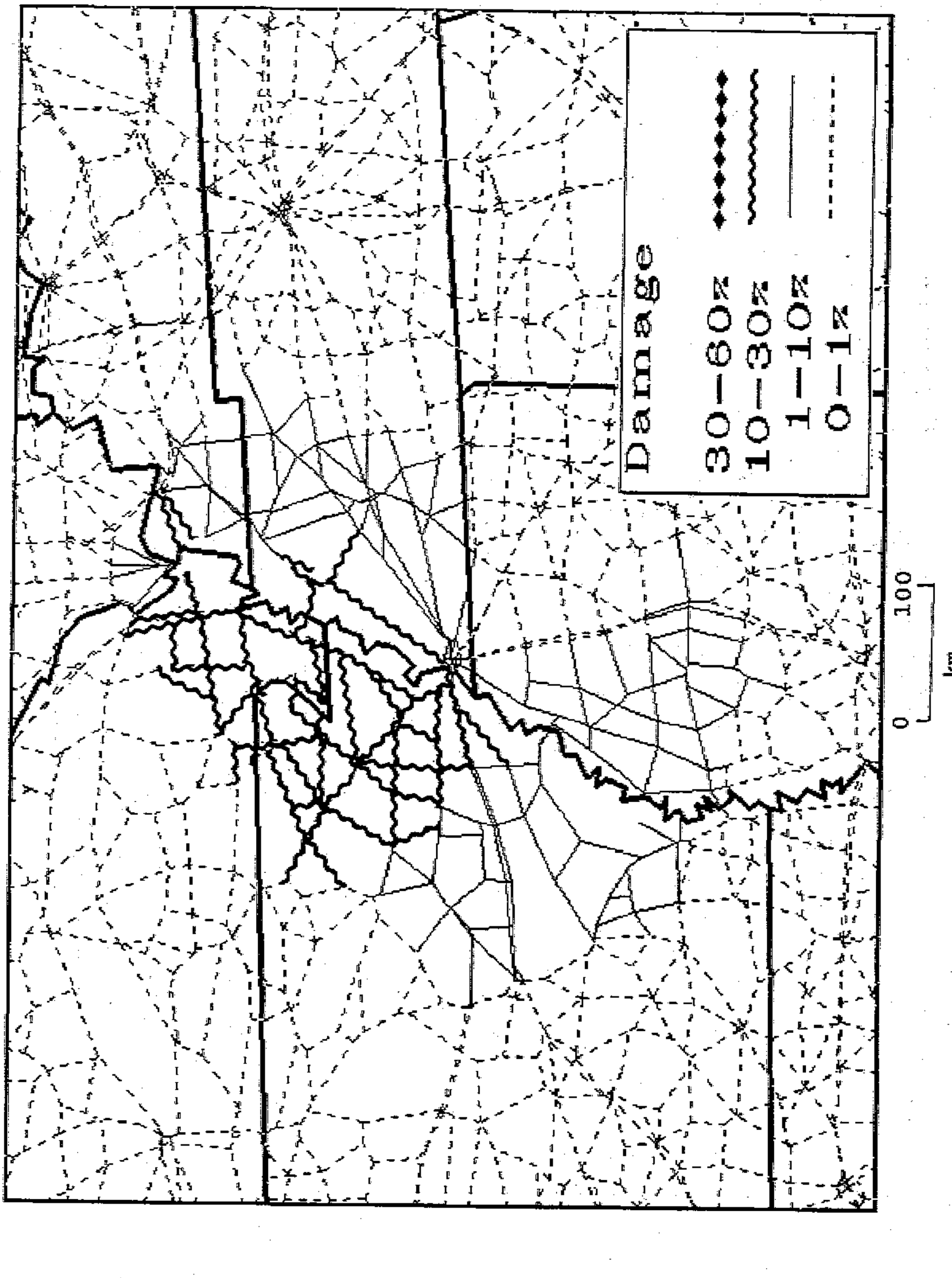

Figure 5-13 *Damage to highways following New Madrid event (M=8.0).*

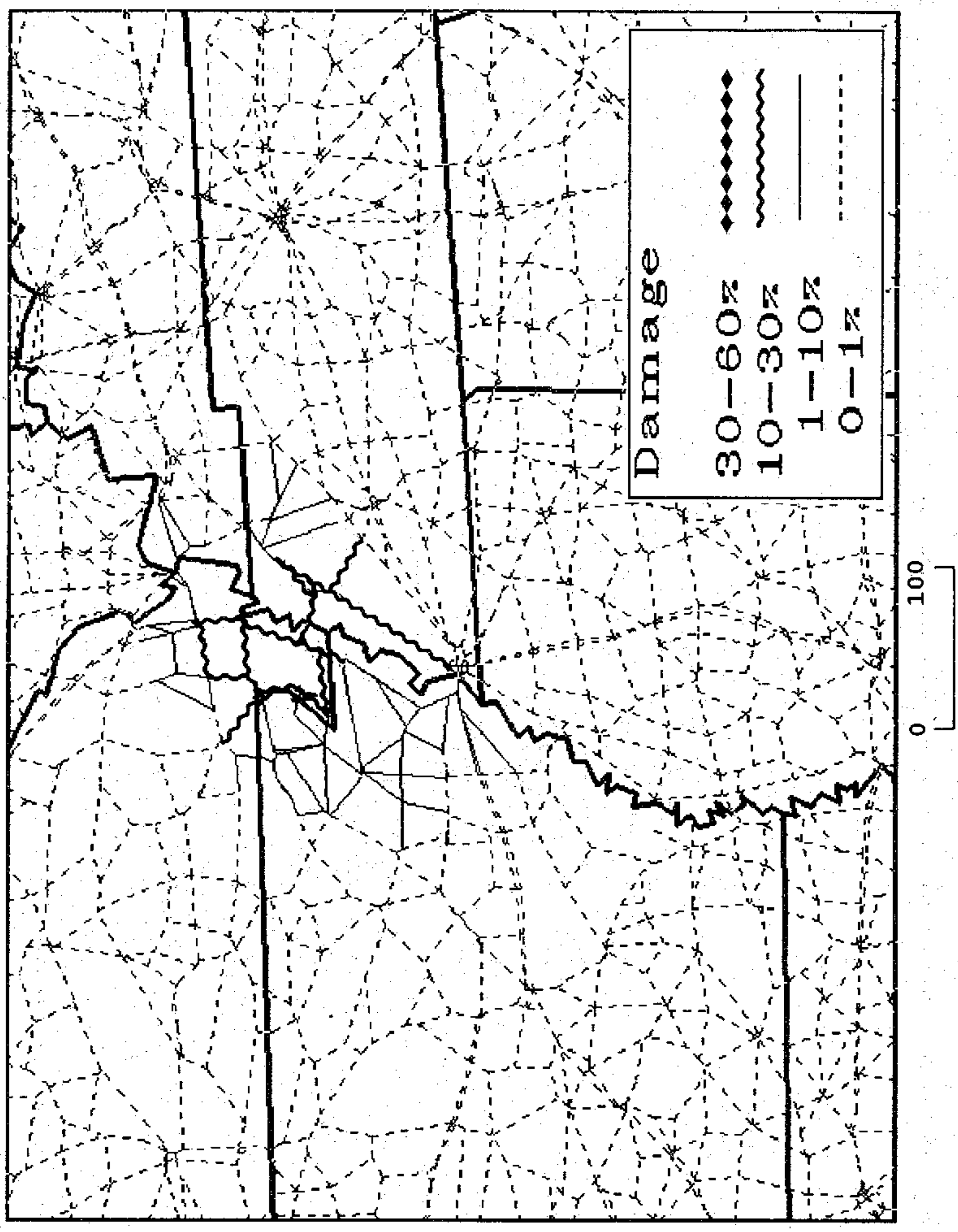

Figure 5-14 *Damage to highways following New Madrid event (M=7.0).*

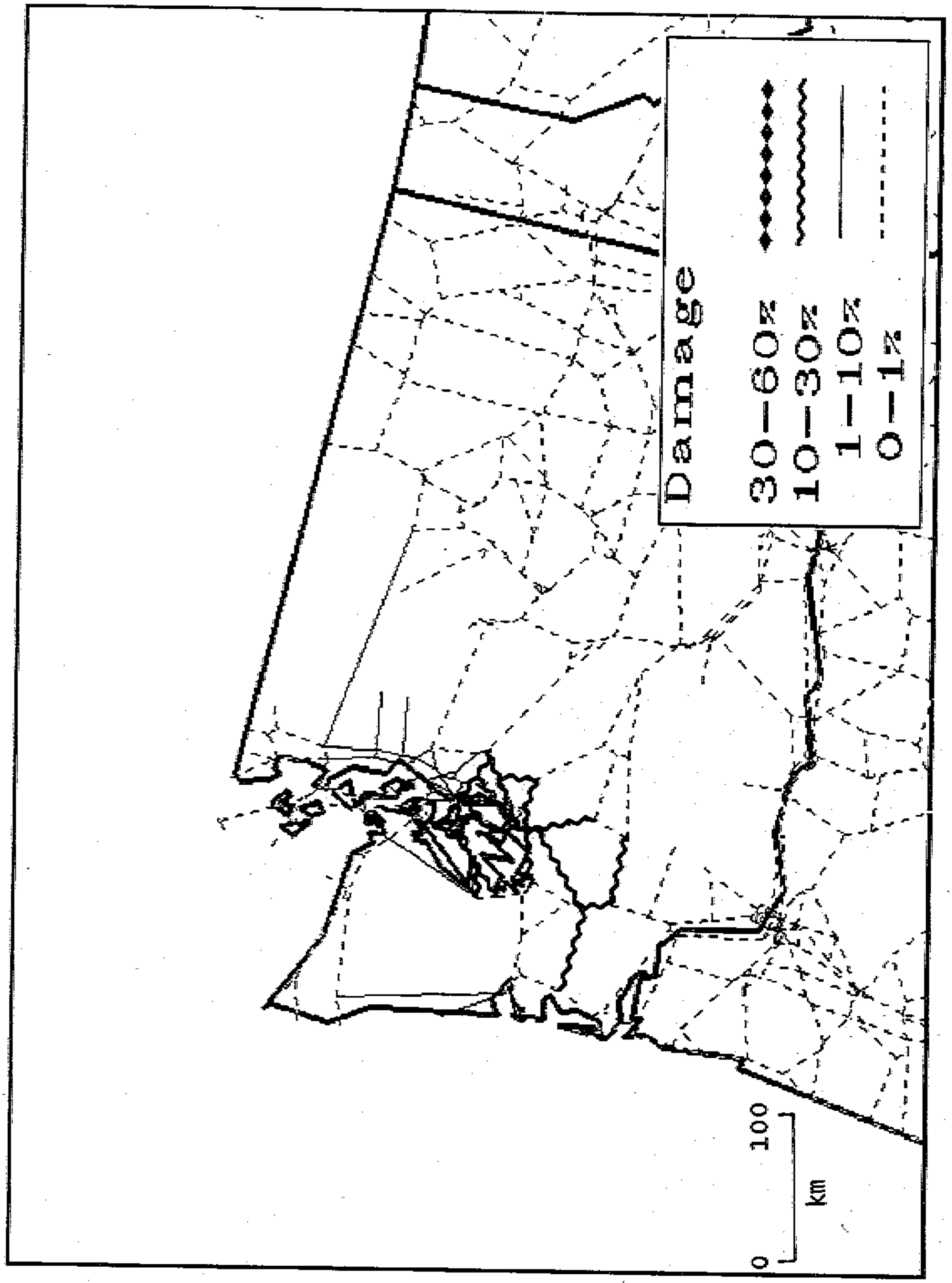

Figure 5-15 Damage to highways following Puget Sound event (M=7.5).

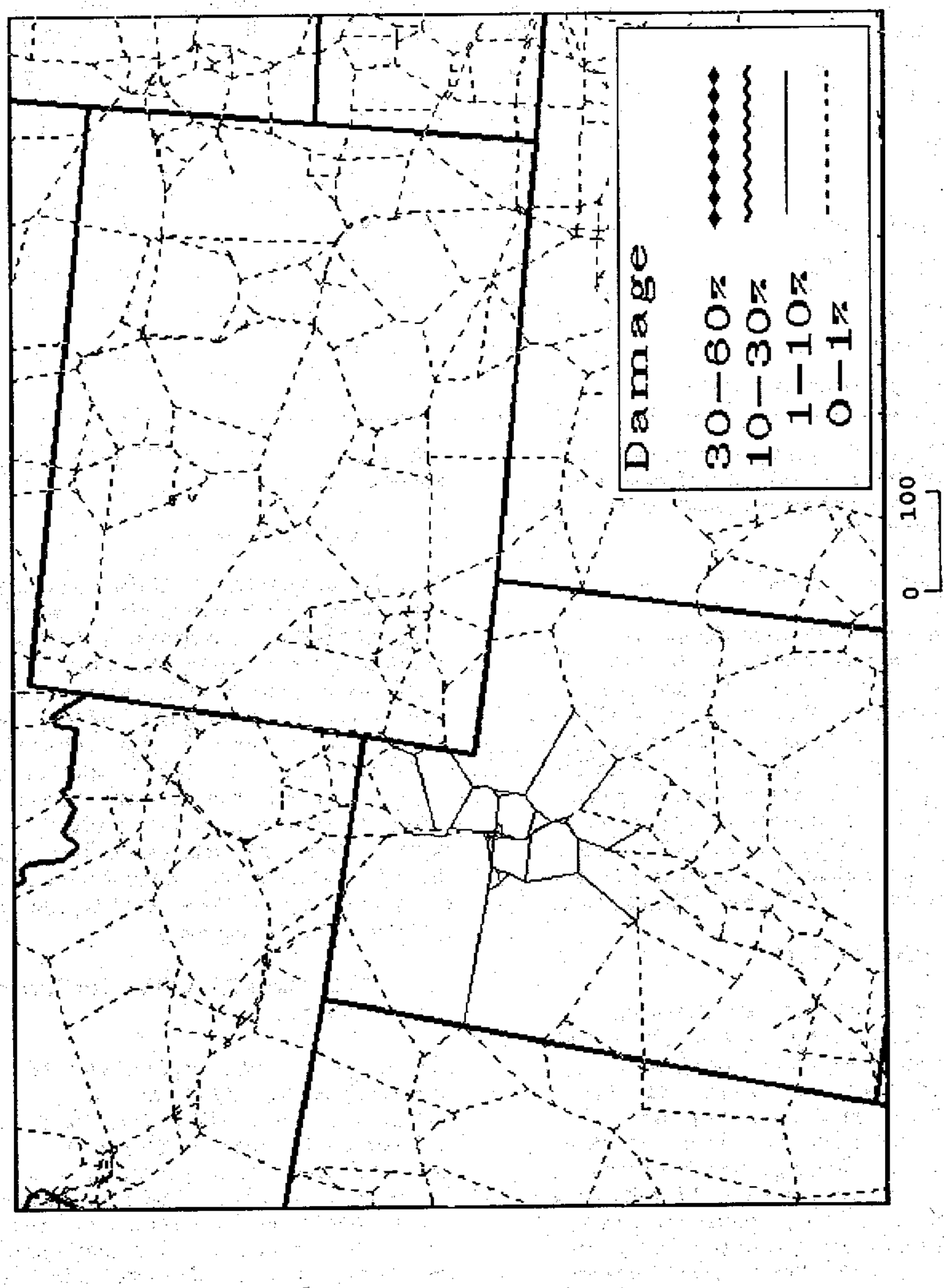

Figure 5-16 Damage to highways following Wasatch Front event (M=7.5).

Table 5-10 Damage to Electric Transmission Lines (Length of Line, Km)

Event	Light Damage 1-10%	Moderate 10-30%	Heavy 30-60%	Major to Destructive 60-100%
Cape Ann	275	0	0	0
Charleston	4,840	27	0	0
Fort Tejon	6,645	1,370	0	0
Hayward	6,320	0	0	0
New Madrid (M=8.0)	6,840	800	0	0
New Madrid (M=7.0)	2,610	0	0	0
Puget Sound	3,860	0	0	0
Wasatch Front	1,370	0	0	0

Total System Length = 441,981 km

Hayward scenario events, respectively. Maps provided in Figures 5-25 and 5-26 show plots of damage to water aqueduct systems for these two California events.

5.4.5 Crude Oil System

Direct damage to the crude oil system, estimated using damage curves for transmission pipelines and the special probabilistic model for pipelines described above, are plotted in Figures 5-27 through 5-29. Data are included for only those events for which damage to this facility type is expected: the two New Madrid events and the Fort Tejon earthquake. Figures 5-27 through 5-29 show pipeline section(s) damaged due to the magnitude-8.0 New Madrid, Fort Tejon, and magnitude-7.0 New Madrid events.

5.4.6 Refined Oil System

Direct damage to the refined oil system, estimated using damage curves for transmission pipelines and refineries and the special probabilistic model for pipelines described above, are plotted in Figures 5-30 and 5-31. These plots indicate that one major section of pipeline would be damaged, with probability of 60% or greater, due to the New Madrid events. We note also that a major refinery (capacity 150,000 barrel/day) would sustain light damage (1-to-10 %) due the Hayward event, and two major refineries with capacities of 420,000 and 100,000 barrels/day, respectively, would sustain light damage due to the Fort Tejon and Puget Sound events.

5.4.7 Natural Gas System

As in the case of crude and refined oil pipelines, direct damage to the natural gas system was estimated using damage curves for transmission pipelines and the special probabilistic model for pipelines described above. Damage to this facility type, plotted in Figures 5-32 through 5-37, is expected for six of the eight scenario earthquakes; excluded are the Charleston and Cape Ann scenario events for which direct damage to natural gas pipelines is estimated to be zero. Broken pipelines shown (Figures 5-32 through 5-37) are node-to-node sections having one or more links estimated as damaged with a probability of 60% or greater.

5.5 Dollar Loss Resulting from Direct Damage

The total direct damage dollar loss for the various lifeline systems and scenario earthquakes were calculated on the basis of the damage statistics summarized above and assumed replacement costs for the lifeline facility types considered (Table 5-13). Assumed replacement cost values are based on data collected for various facility sizes and regions, which were then weighted to account for the estimated distribution of facility sizes in the national database.

Table 5-11 Damage Percent for Electric Transmission Substations for Each Scenario Earthquake (Percent of Substations in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Indiana 89	Mississippi 93	South Carolina 100	North Carolina 76	Georgia 86
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	14%	8%	22%	16%	24%	2%	63%	43%	20%	33%
Heavy 30-60 %	0%	0%	10%	9%	7%	0%	8%	14%	0%	3%
Major to Destructive 60-100 %	0%	8%	29%	6%	1%	0%	10%	16%	1%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 153	Connecticut 69	Delaware 3	Rhode Island 22	New Hampshire 22	Utah 10
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	82%	42%	33%	100%	45%	30%
Heavy 30-60 %	0%	0%	0%	0%	0%	20%
Major to Destructive 60-100 %	5%	0%	0%	0%	0%	10%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 205	California 205	Washington 155	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Mississippi 93
Light Damage 1-10 %	8%	11%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	13%	6%	12%	0%	2%	21%	16%	16%	14%
Heavy 30-60 %	14%	< 1%	3%	0%	0%	16%	0%	0%	2%
Major to Destructive 60-100 %	13%	12%	43%	0%	6%	6%	3%	0%	0%

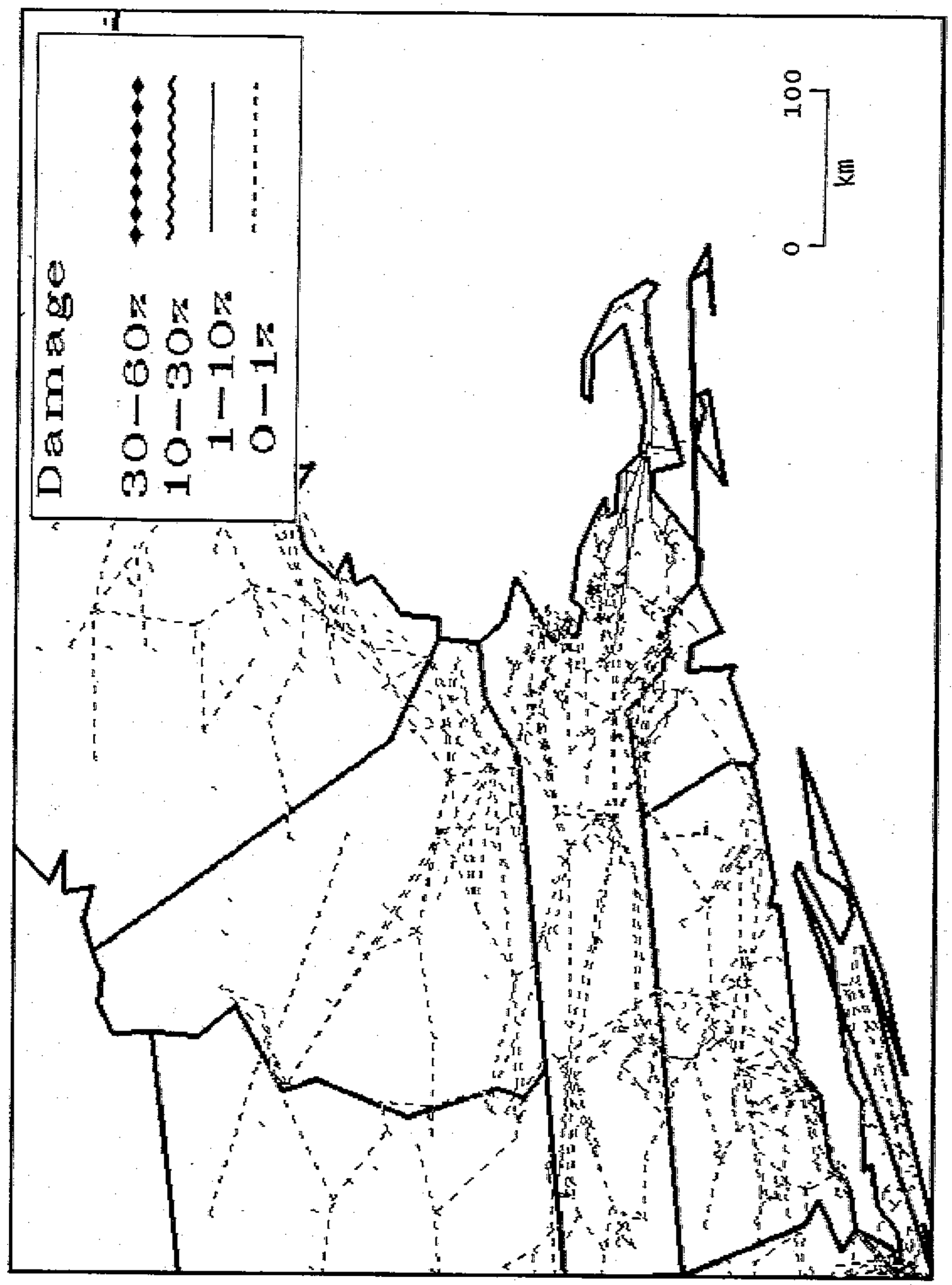

Figure 5-17 *Damage to electric power transmission lines following Cape Ann event (M=7.0).*

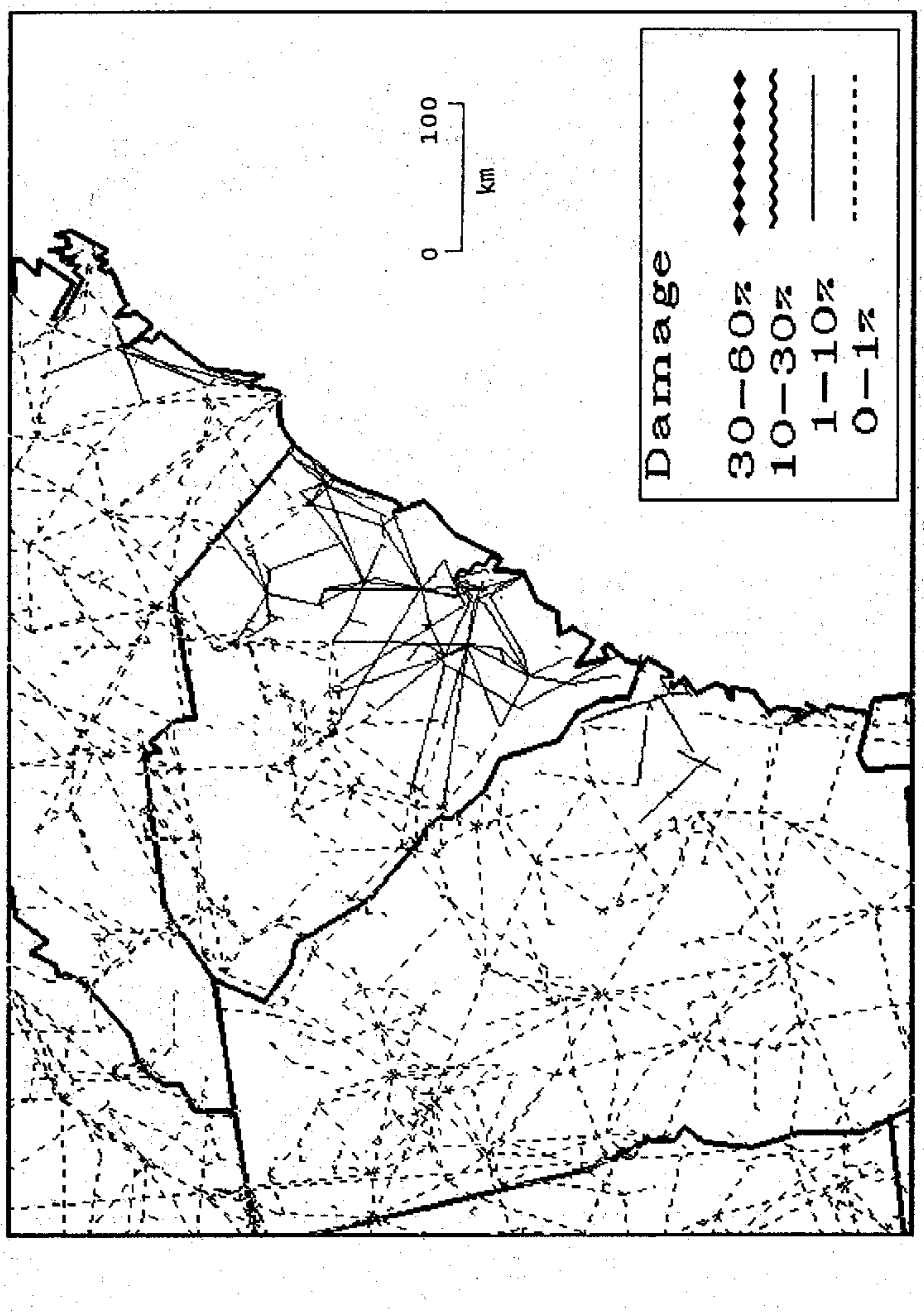

Figure 5-18 *Damage to electric power transmission lines following Charleston event (M=7.5).*

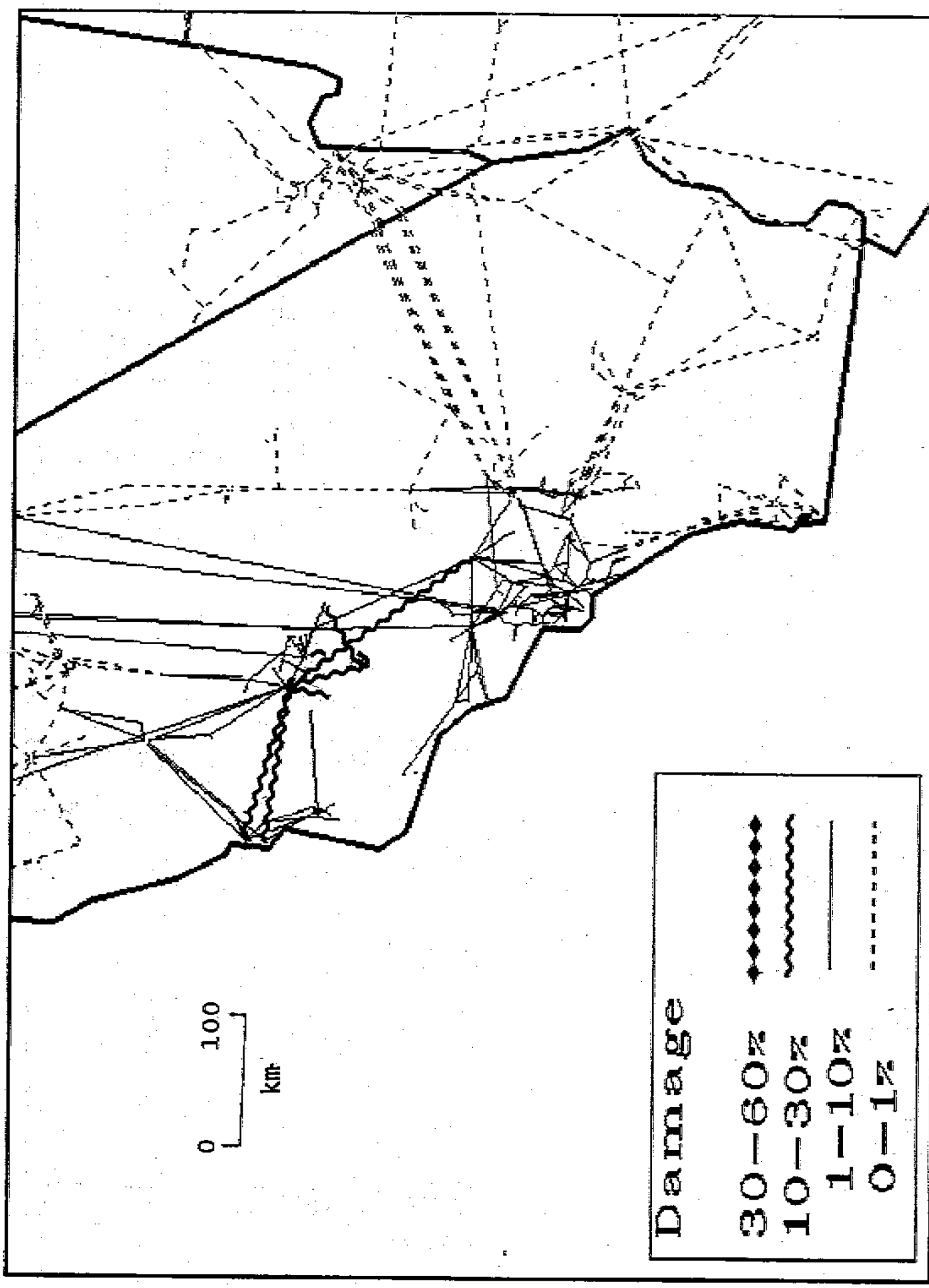

Figure 5-19 *Damage to electric power transmission lines following Fort Tejon event (M=8.0).*

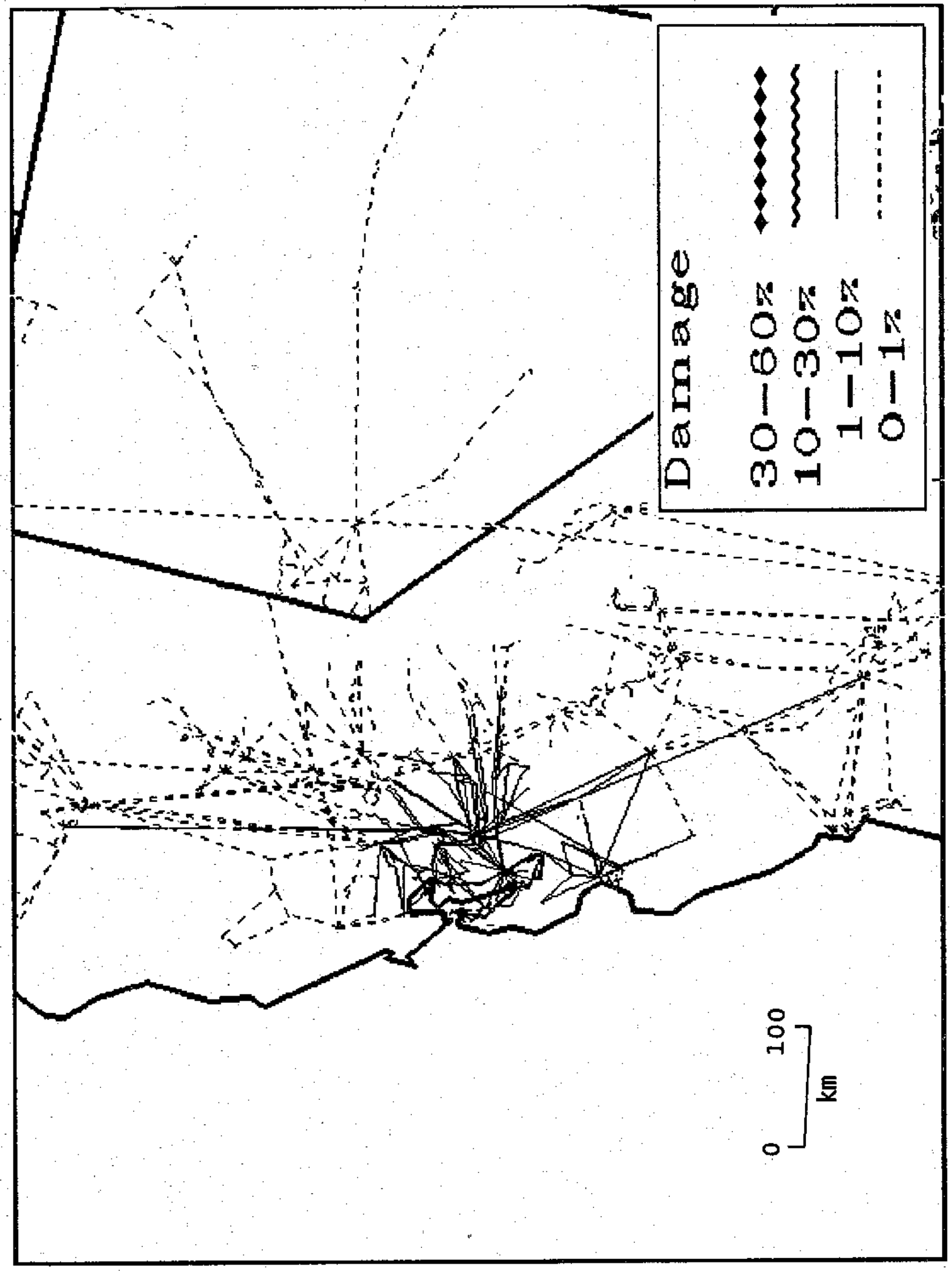

Figure 5-20 Damage to electric power transmission lines following Hayward event (M=7.5).

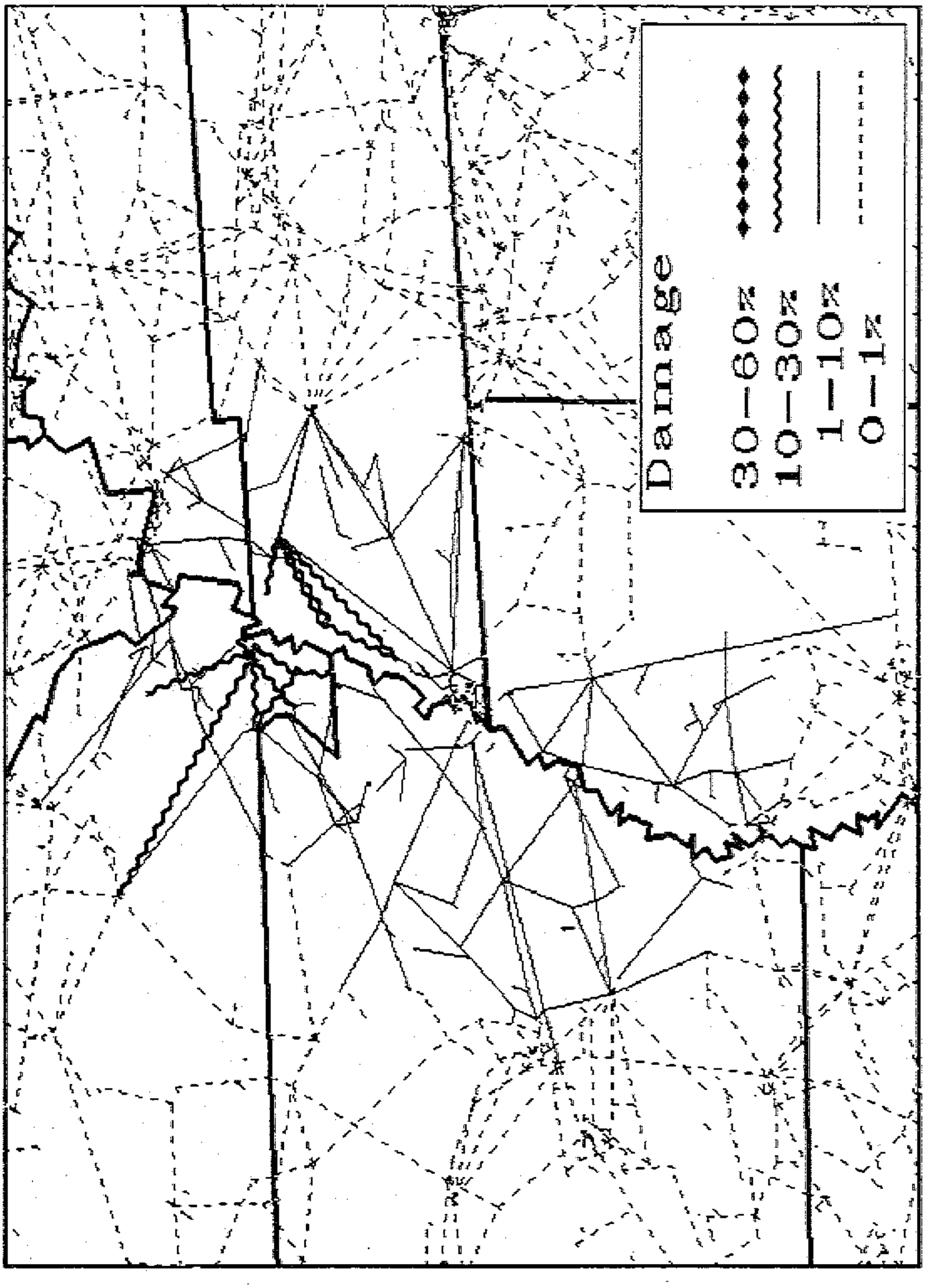

Figure 5-21 Damage to electric power transmission lines following New Madrid event (M=8.0).

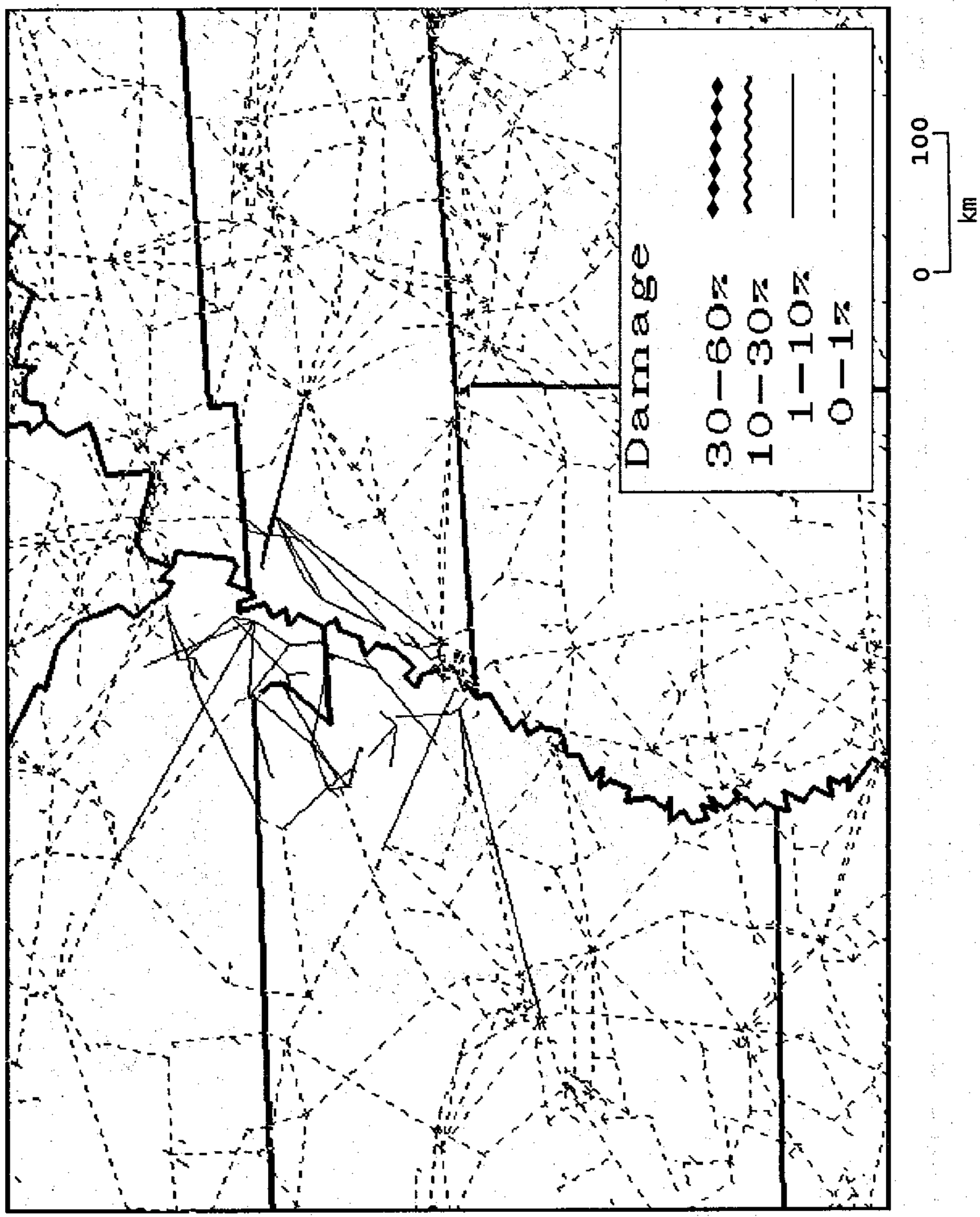

Figure 5-22 Damage to electric power transmission lines following New Madrid event (M=7.0).

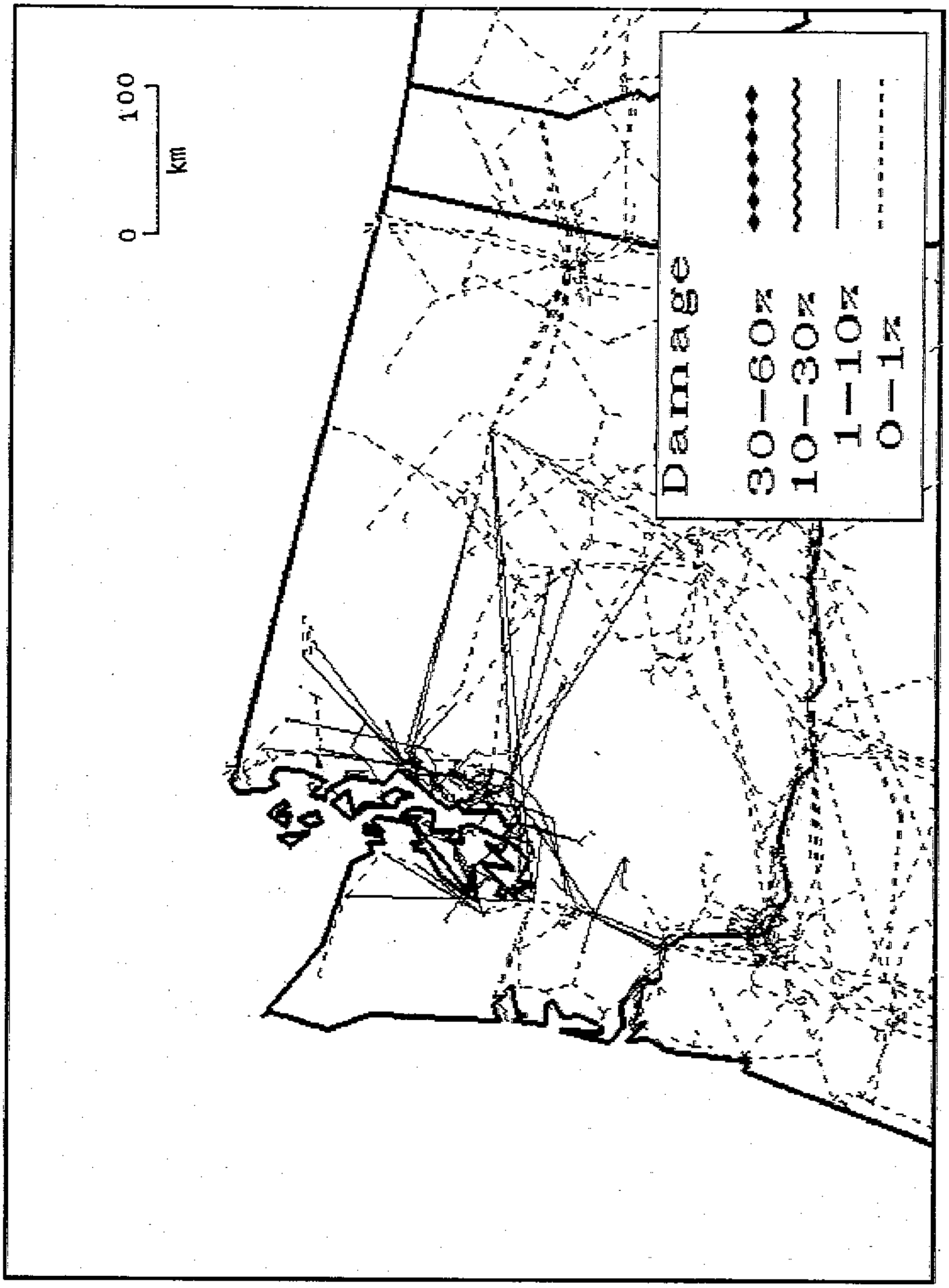

Figure 5-23 *Damage to electric power transmission lines following Puget Sound event (M=7.5).*

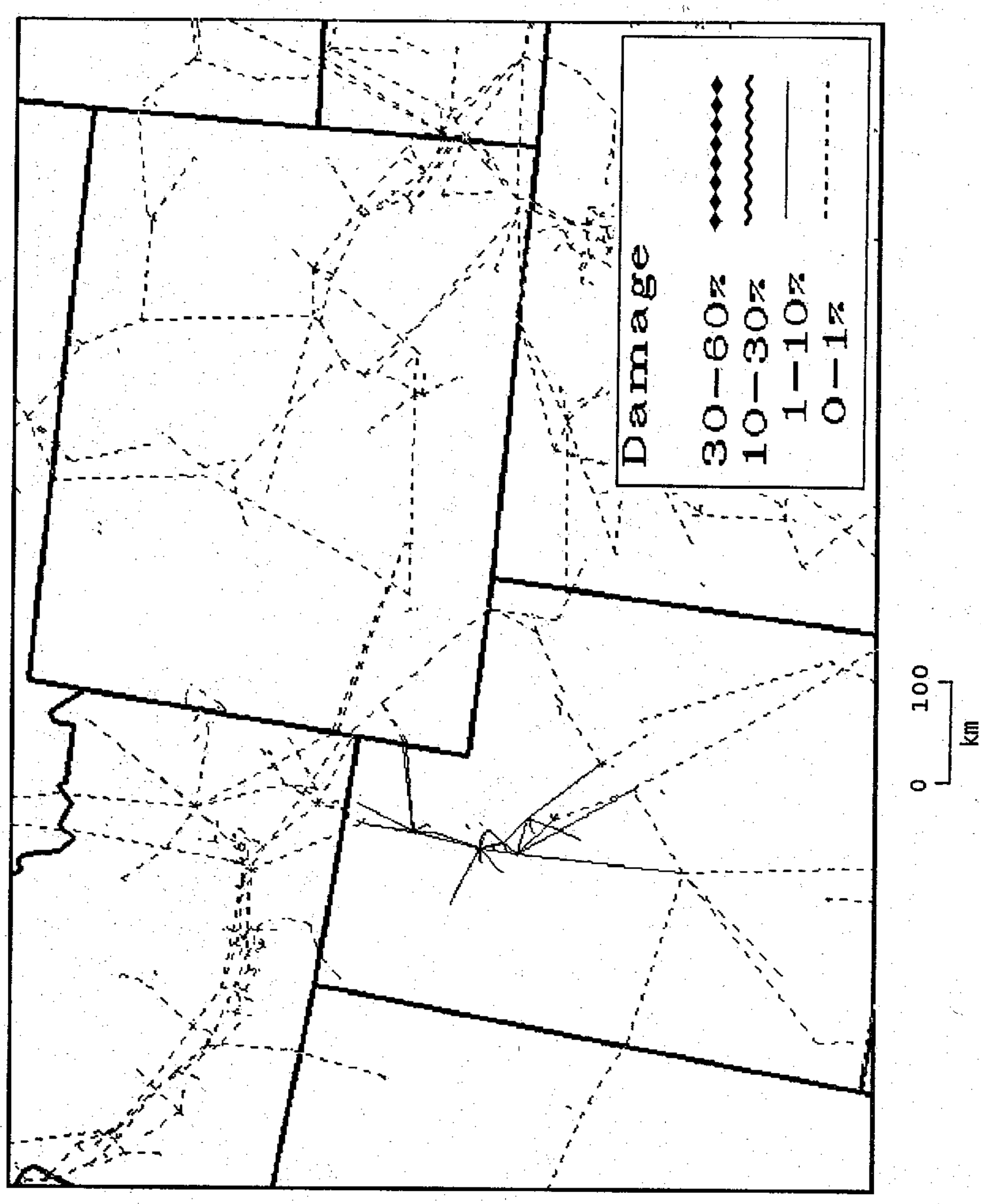

Figure 5-24 Damage to electric power transmission lines following Wasatch Front event (M=7.5).

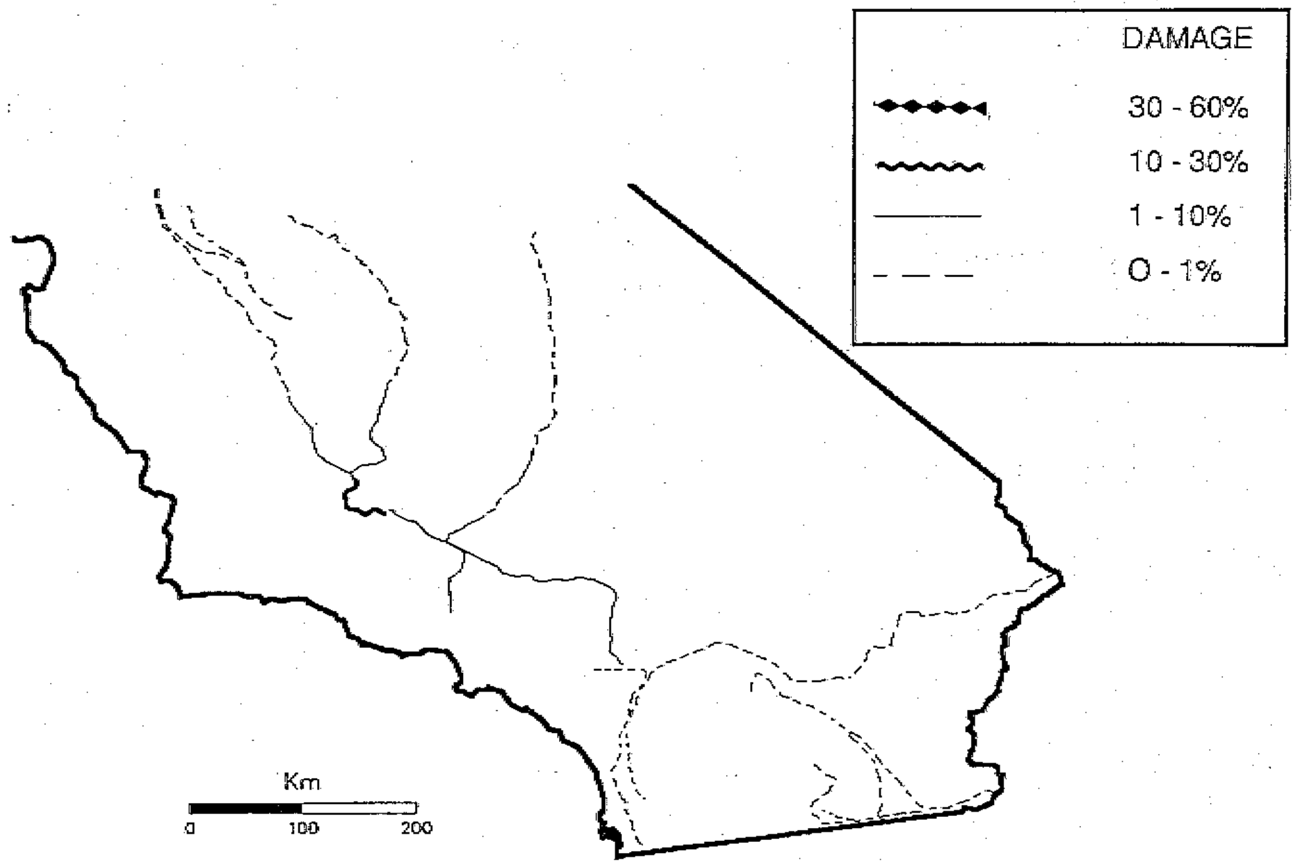

Figure 5-25 *Damage to water aqueduct system following Fort Tejon event (M=8.0).*

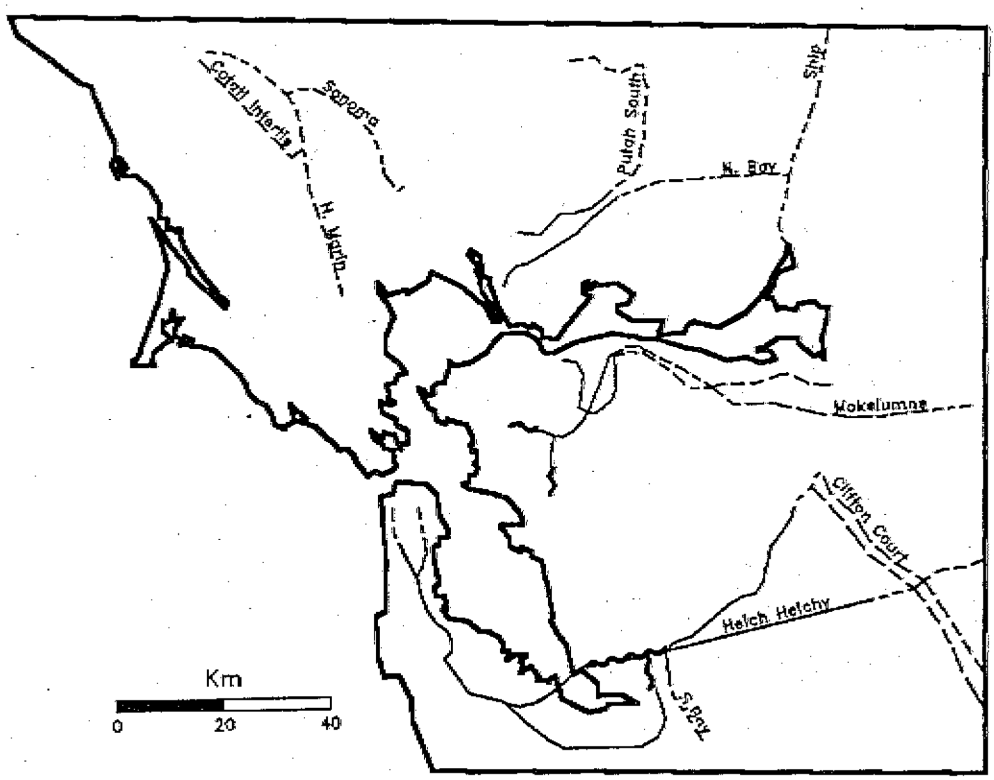

Figure 5-26 *Damage to water aqueduct system following Hayward event (M=7.5).*

Table 5-12 Damage to Water Aqueduct System (Length of Aqueduct, Km)

Event	*Light Damage 1-10%*	*Moderate 10-30%*	*Heavy 30-60%*	*Major to Destructive 60-100%*
Fort Tejon	350	36	2	0
Hayward	240	20	1	0
Puget Sound	60	0	0	0

Table 5-13 Cost Estimates for Lifeline Components

System	*Component*	*Cost Estimate**
Railway	Tracks/Roadbeds	$500,000/mile**
Highway	Conventional highway bridge	$1,200,000
	Freeway/Highway	$1,400,000/mile**
	Local Roads	$300,000/mile**
Air Transportation	Terminals	$4,000,000
	Runways/Taxiways	$1,000,000/runway
Sea/Water Transportation	Ports/Cargo Handling Equipment	$20,000,000
Electric	Distribution Lines	$150,000/mile**
	Transmission Lines	$500,000/mile**
	Transmission Substations	$400/person***
Water Supply	Transmission Aqueducts	$5,000,000/mile**
Natural Gas	Transmission Aqueducts	$300,000/mile**
Petroleum Fuels	Transmission Pipelines	$300,000/mile**
Emergency Service	Medical Care Facilities (assumes 85,000 square foot average size)	$35,000,000
	Fire Stations (assumes 5,000 square foot average size)	$400,000
	Police Stations (assumes 11,000 square foot average size)	$1,000,000

*1991 Dollars
**1 mile = 1.609 km.
***in service area

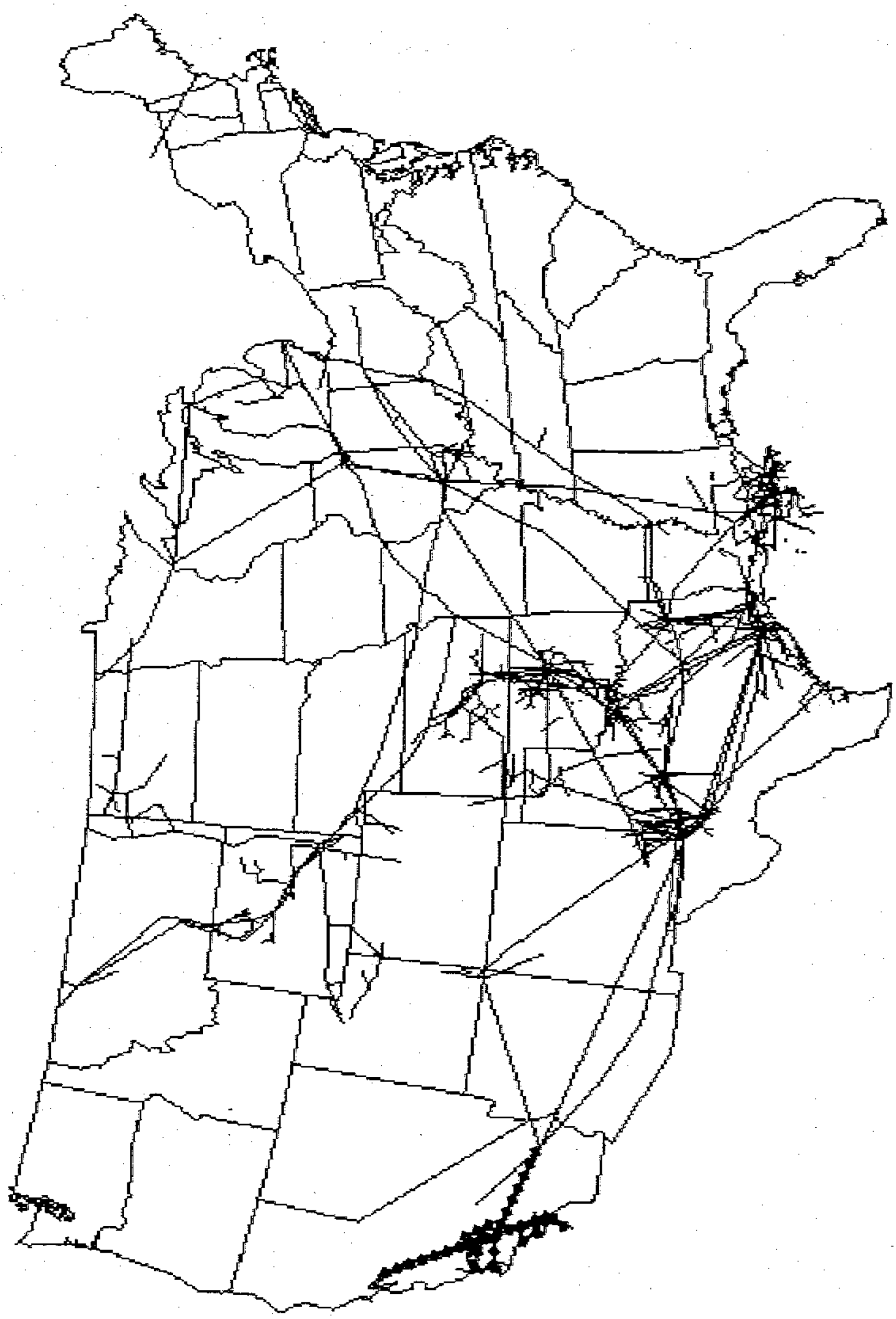

Figure 5-27 *Damage to crude oil system following Fort Tejon event (M=8.0). Broken pipelines are shown with solid diamonds.*

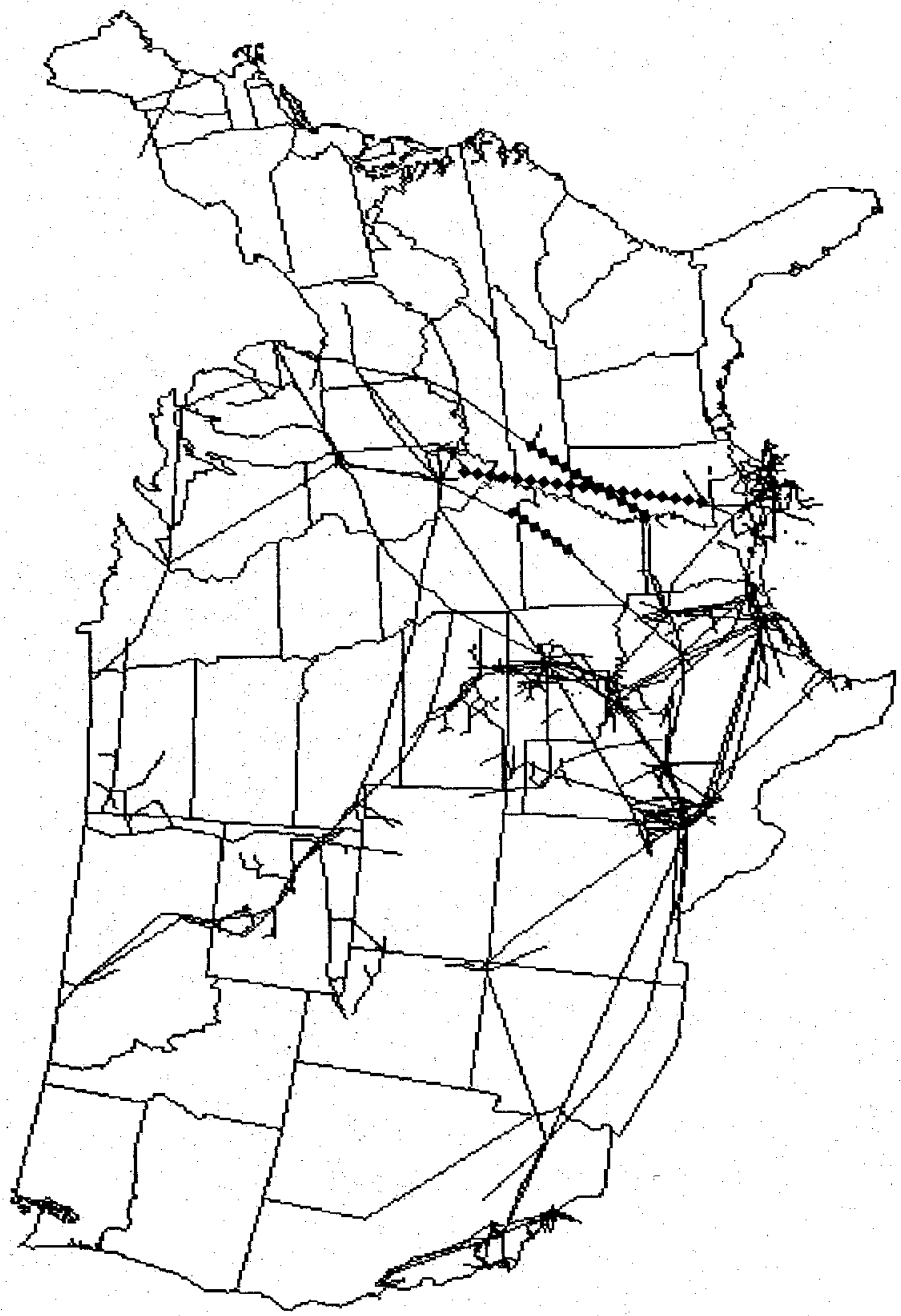

Figure 5-28 Damage to crude oil system following New Madrid event (M=8.0). Broken pipelines are shown with solid diamonds.

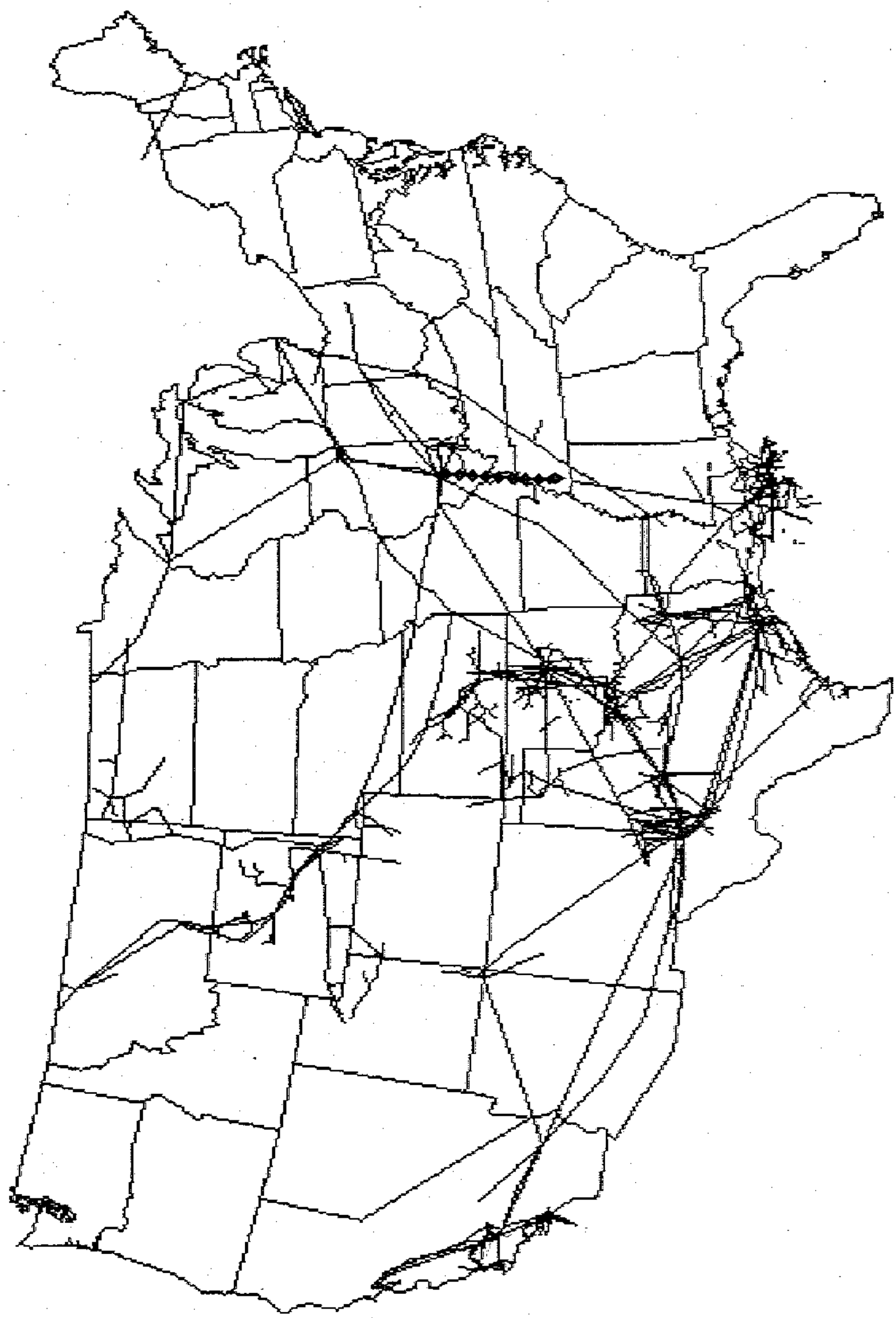

Figure 5-29 *Damage to crude oil system following New Madrid event (M=7.0). Broken pipelines are shown with solid diamonds.*

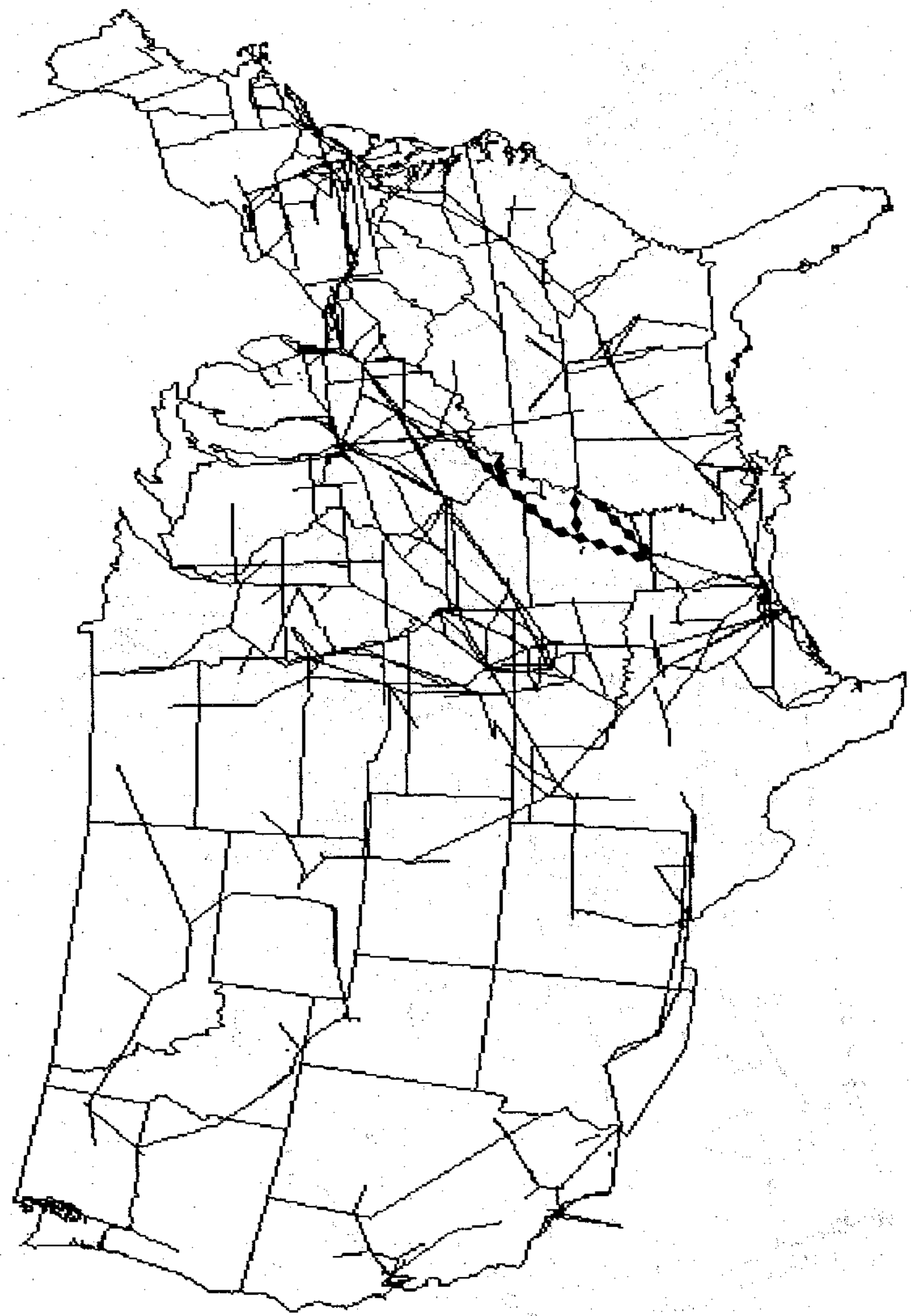

Figure 5-30 *Damage to refined oil system following New Madrid event (M=8.0). Broken pipelines are shown with solid diamonds.*

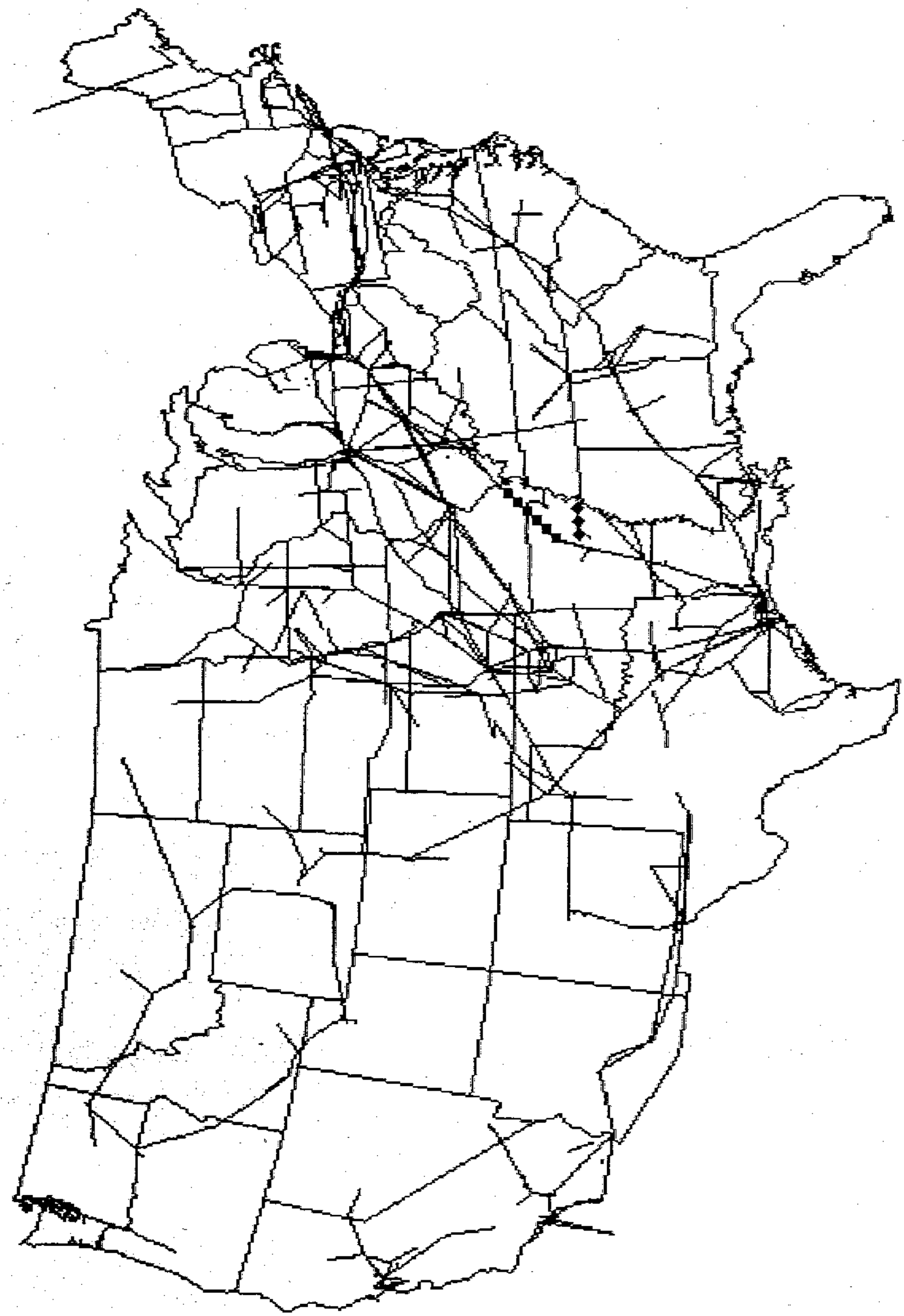

Figure 5-31 *Damage to refined oil system following New Madrid event (M=7.0). Broken pipelines are shown with solid diamonds.*

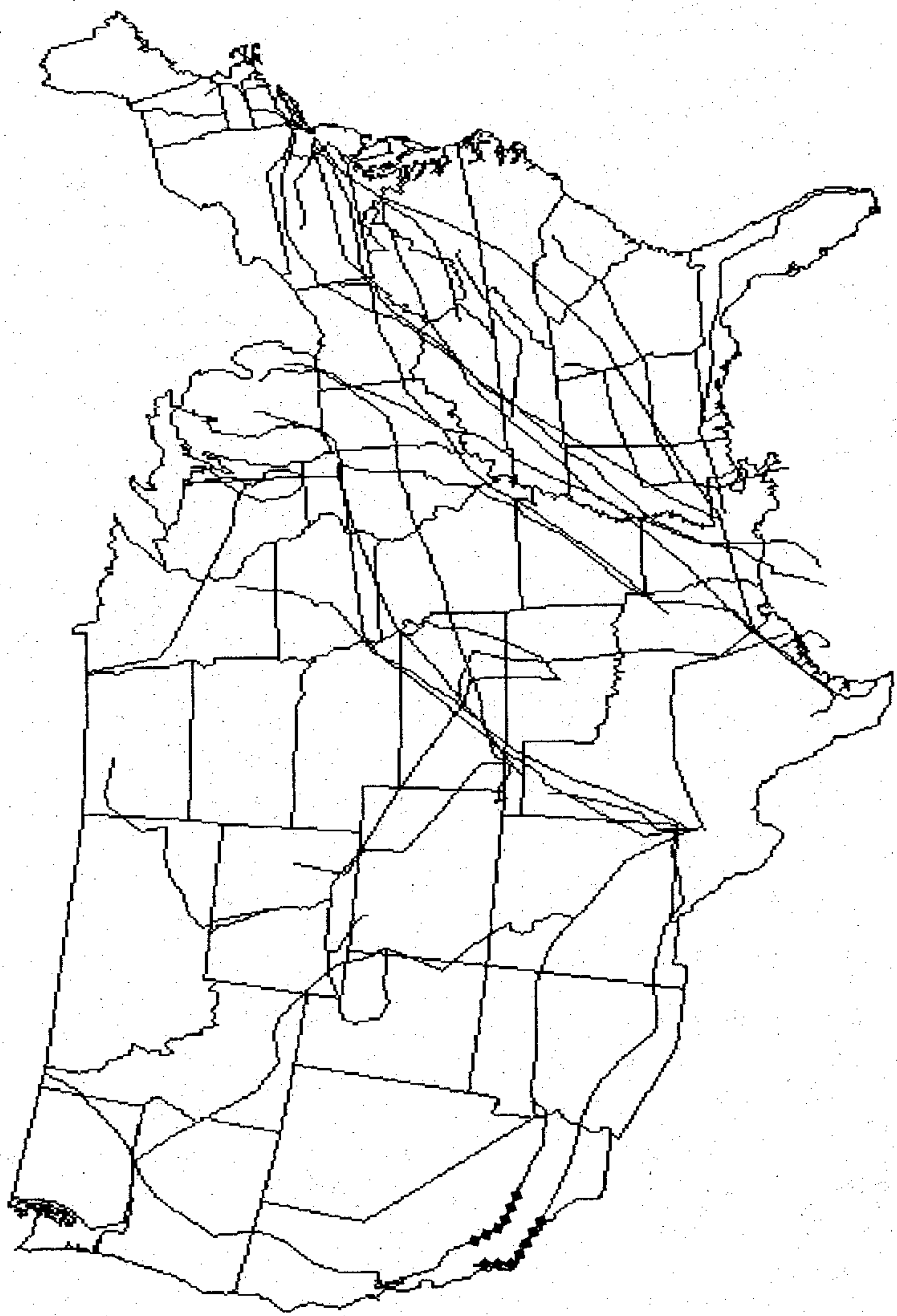

Figure 5-32 *Damage to natural gas system following Fort Tejon event (M=8.0). Broken pipelines are shown with solid diamonds.*

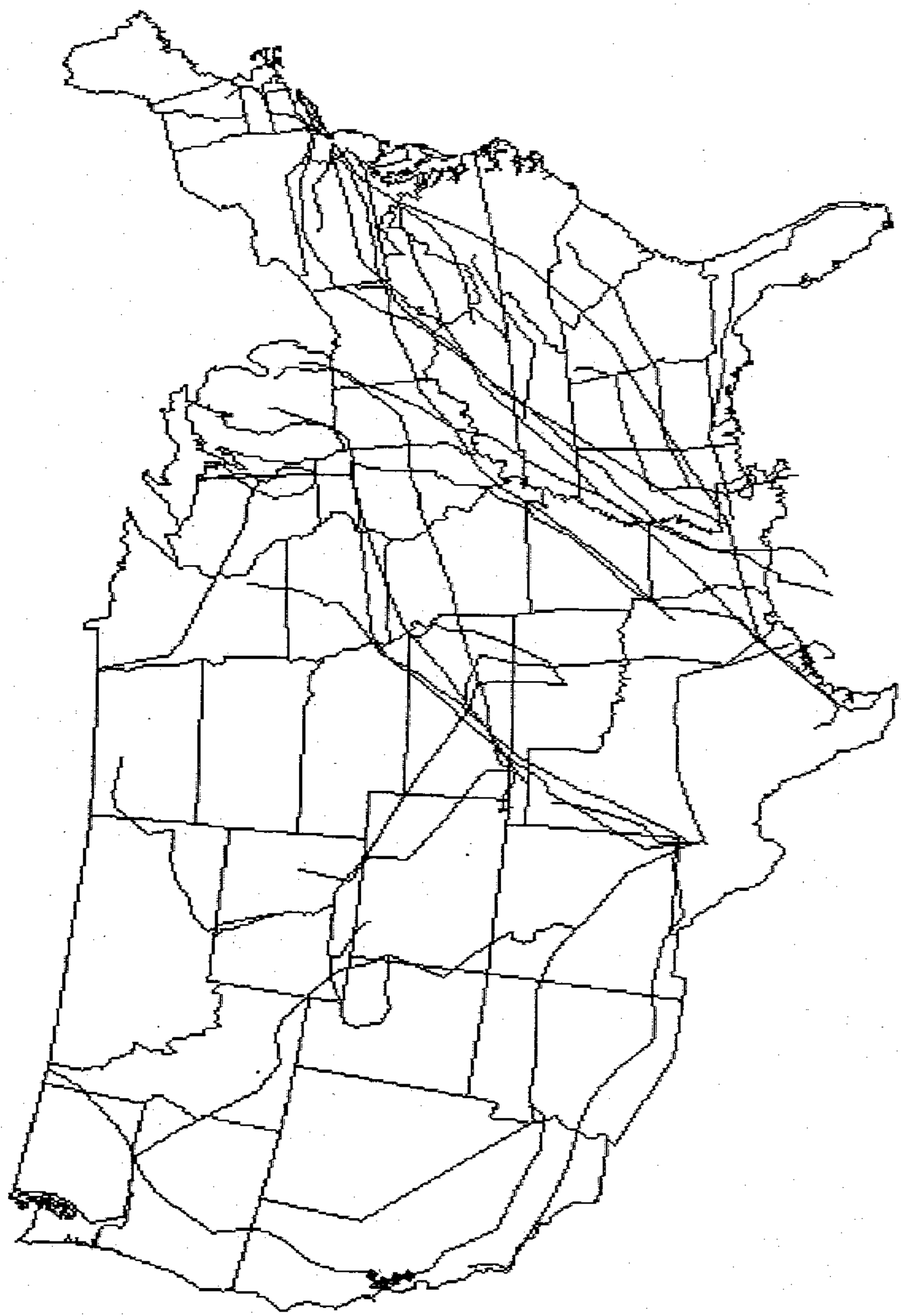

Figure 5-33 *Damage to natural gas system following Hayward event (M=7.5). Broken pipelines are shown with solid diamonds.*

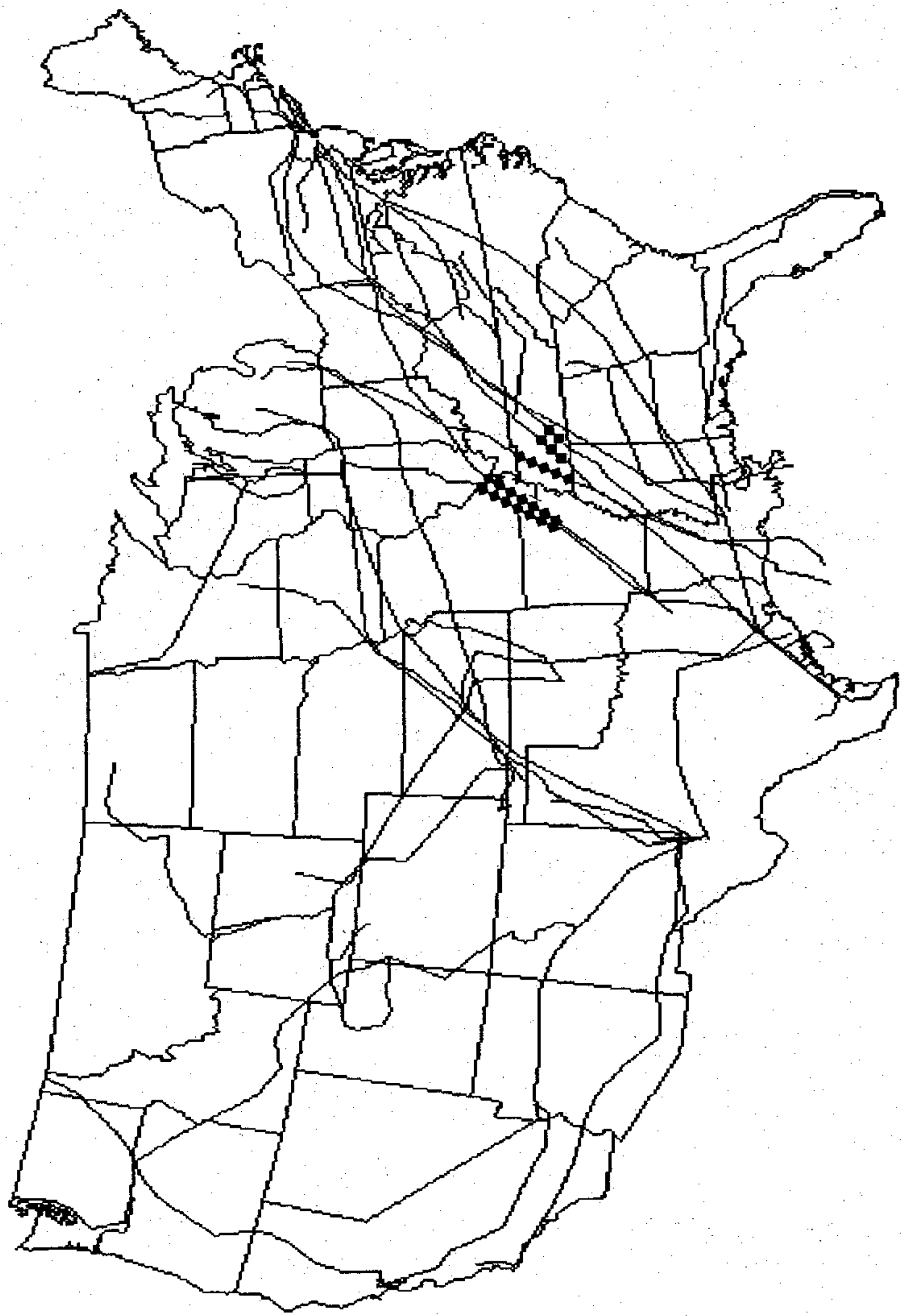

Figure 5-34 *Damage to natural gas system following New Madrid event (M=8.0). Broken pipelines are shown with solid diamonds.*

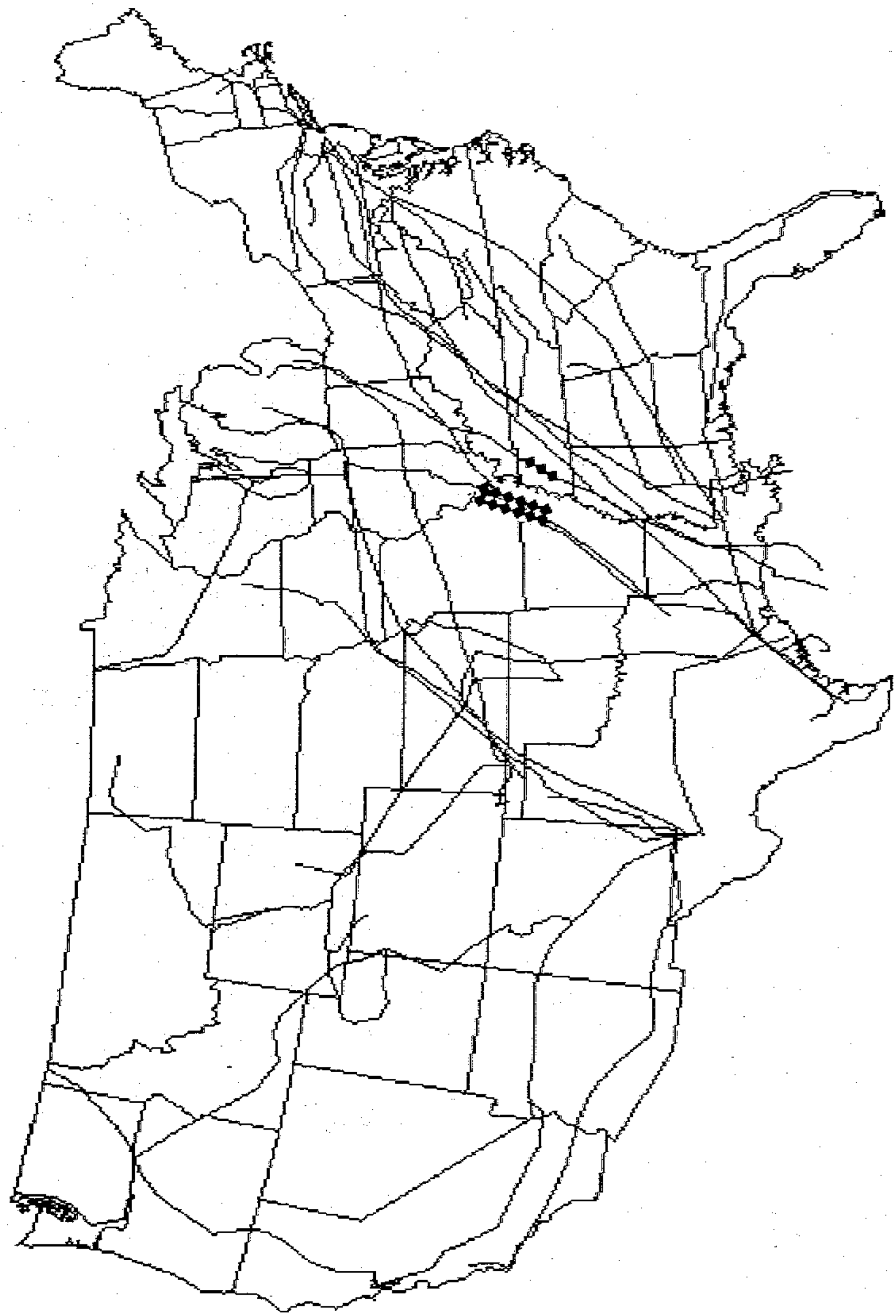

Figure 5-35 *Damage to natural gas system following New Madrid event (M=7.0). Broken pipelines are shown with solid diamonds.*

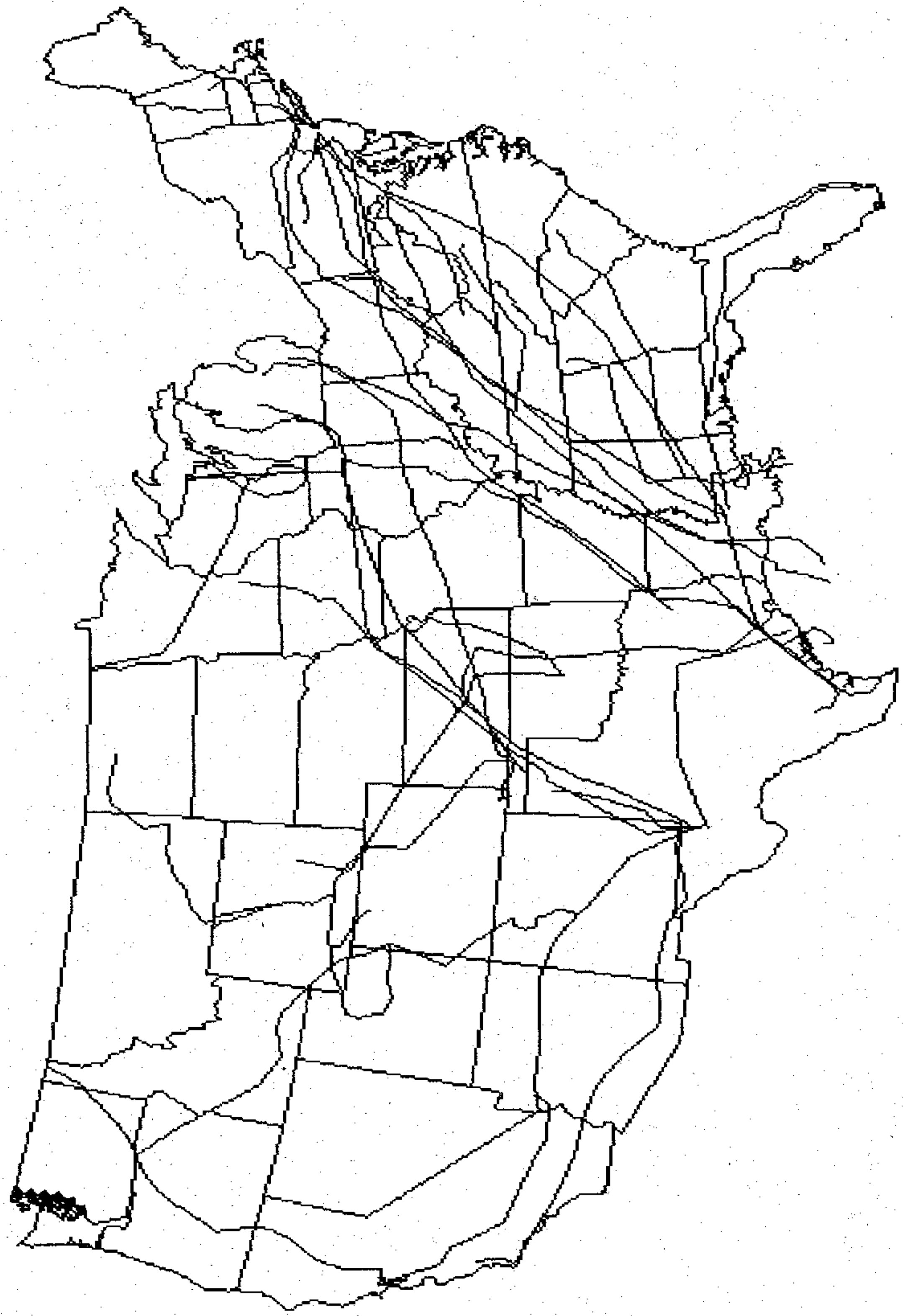

Figure 5-36 Damage to natural gas system following Puget Sound event (M=7.5). Broken pipelines are shown with solid diamonds.

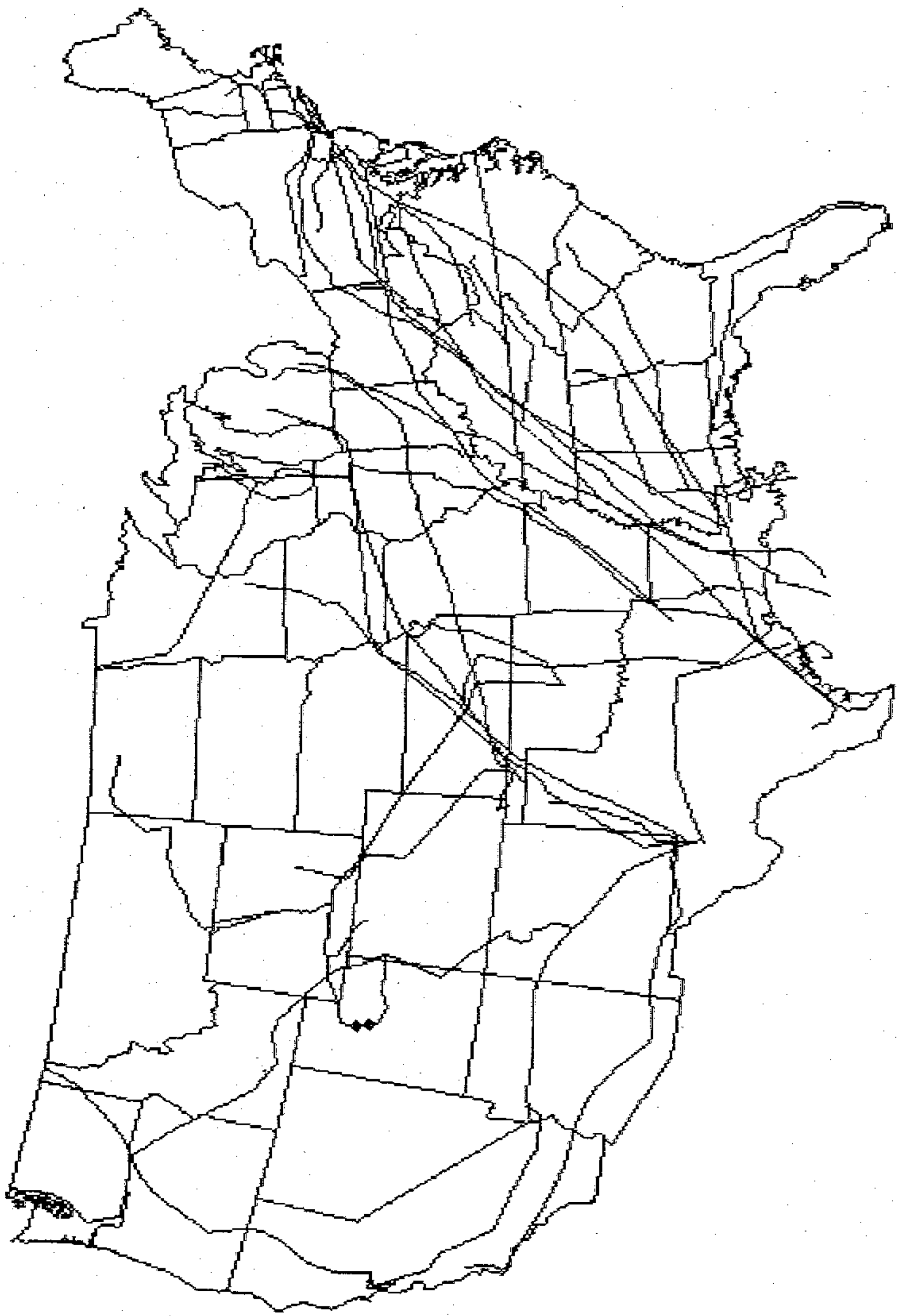

Figure 5-37 *Damage to natural gas system following Wasatch Front event. Broken pipelines are shown with solid diamonds.*

Summaries of dollar loss estimates for direct damage to site-specific systems and extended regional lifeline networks during the eight scenario earthquakes are provided in Table 5-14. Estimated dollar losses due to direct damage to local electric, water, and highway distribution systems are provided in Table 5-15. We note that damage distribution dollar loss estimates for direct damage to local distribution systems were estimated using cost data from Table 5-13 and damage curves from Appendix B for electric distribution lines, local roads, and water trunk lines. Intensities were estimated at the center of the Standard Metropolitan Statistical Areas, assuming the distribution systems were lumped at these locations.

The estimates provided in Tables 5-14 and 5-15 are based on the available inventory data and other assumptions and models described in this report. As a result, the accuracy of these estimates may vary from lifeline to lifeline. Estimates for electric systems, in particular, are believed to be more sensitive to the lack of capacity information than are the other lifelines.

By combining the data from Tables 5-14 and 5-15, we estimate the total direct damage dollar losses (in billions of U. S. dollars) for the eight scenario earthquakes as follows:

Earthquake	Direct Dollar Loss (in Billions, 1991$)
Cape Ann	$4.2
Charleston	$4.9
Fort Tejon	$4.9
Hayward	$4.6
New Madrid, M = 8.0	$11.8
New Madrid, M = 7.0	$3.4
Puget Sound	$4.4
Wasatch Front	$1.5

5.6 Comparison with Previous Studies

The foregoing presents a methodology and results for understanding the direct damage impacts of earthquakes on U.S. lifelines. No previous study has examined lifelines in comparable breadth or scale, so that comparisons are difficult. Several studies have examined the effect of earthquakes on lifelines for various regions, including:

- Earthquake Vulnerability Analysis of the Charleston, South Carolina Area (Citadel, 1988),
- Earthquake Planning Scenario for a Magnitude 7.5 Earthquake on the Hayward Fault in the San Francisco Bay Area (Steinbrugge et al., 1987) (representative of several studies in California, including others for the Newport Inglewood Fault Zone, the San Andreas Fault in northern and southern portions of California (e.g., Davis et al., 1982),
- A study of the Wasatch Front, Utah, water and gas systems (Taylor, Wiggins, Harper and Ward, 1986), and
- A pilot study on vulnerability of crude oil transmission systems in the New Madrid area (Ariman, et al., 1990).

Compared to the present study, these previous studies were typically limited in being either confined to one or a few lifelines, qualitative rather than quantitative, and/or geographically localized. Nevertheless, to the extent possible, comparison of this study's results with that of previous studies is of value, in order to compare each aspect of the methodology. The Charleston, South Carolina study is recent, probably the most comprehensive of the studies in scope, and provides quantitative results. We therefore next examine that study and its results, vis-a-vis this study.

Comparison with a study on the Charleston event. Researchers at The Citadel, the Military College of South Carolina, estimated damage to critical facilities and other resources in the epicentral region, assuming a repeat of the 31 August 1886 Charleston event. The study region comprised three counties of the Charleston, South Carolina area: Charleston County, Berkeley County, and Dorchester County. The Citadel analysis and conclusions appear in *An Earthquake Vulnerability Analysis of the Charleston, South Carolina, Area*, of July 1988. Their methodology relied significantly upon ATC-13 procedures, so The Citadel study and the present study take comparable approaches and use similar classifications for structures and

Table 5-14 Direct Damage Losses ($ Millions)

Scenario	*Highways*	*Electric*	*Fire Stations*	*Broadcasting Station*	*Medical Care*	*Ports*	*Airports*	*Railroads*	*Natural Gas*	*Refined Oil*	*Crude Oil*	*Water*	*Total*
Cape Ann	$382	$1,312	$6	$19	$490	$53	$91	$9	$0	$0	$0	$	2,362
Charleston	$773	$1,264	$9	$68	$565	$380	$142	$156	$0	$0	$0	$.	$3,358
Fort Tejon	$470	$886	$48	$26	$1,431	$170	$148	$158	$11	$0	$28	$140	3,517
Hayward	$208	$1,310	$7	$17	$1,297	$115	$37	$115	$6	$0	$0	$91	3,203
New Madrid 8	$2,216	$2,786	$13	$91	$1,297	$0	$411	$458	$56	$28	$47	$	$7,403
New Madrid 7	$204	$1,077	$3	$34	$396	$0	$145	$108	$19	$9	$19	$	2,013
Puget Sound	$496	$1,834	$13	$49	$507	$196	$210	$96	$6	$0	$0	$18	3,425
Wasatch Front	$323	$90	$2	$44	$205	$0	$29	$31	$6	$0	$0	$	730

Table 5-15 Direct Losses Due to Damage to Distribution Systems

Event	*Electric $ Billion*	*Water $ Billion*	*Highways $ Billion*
Cape Ann	$0.89	$0.30	$0.60
Charleston	0.74	0.31	0.50
Fort Tejon	0.91	0.23	0.23
Hayward	0.90	0.20	0.25
New Madrid (M=8.0)	2.07	0.88	1.40
New Madrid (M=7.0)	0.65	0.28	0.44
Puget Sound	0.58	0.09	0.28
Wasatch Front	0.38	0.13	0.26

structural damage. The Citadel researchers studied direct damage to lifelines, as well as to housing, schools, and other components of the built environment in the three county area, but they did not investigate economic impacts as the current study does.

The following sections compare the assumptions and conclusions of the current study with those of The Citadel researchers. Note that the current study provided aggregate damage for the whole of South Carolina, and damage is not broken out by county, as it is in The Citadel study. Nonetheless, since the three counties enclose the bulk of the damaged South Carolina lifelines, the results should be comparable. The first section compares the scenario earthquake assumed by the two studies. The second section compares the results of the direct damage analyses for lifelines.

Scenario Earthquake. The Citadel researchers employed more severe ground shaking than the current study's use of the Evernden Model produced for the same event. The Citadel posted MMI IX to MMI X ground shaking within 25 miles of the epicenter, MMI VII to MMI VIII ground shaking within a 100 mile outer radius, and MMI VI or less ground shaking beyond this. This agrees well with a *broad* regional isoseismal map based on the historical record presented by Bollinger (1977). This broad map was developed by enveloping a detailed map also developed by Bollinger (1977) (i.e., the broad map was developed by the maximum MMI within a region taken from the detailed map, and using that as the MMI value for the broad map--both maps are presented in Figure 4-6). The Evernden Model used in the current study provided estimates of ground shaking on a detailed scale similar to that of the detailed map by Bollinger. In the Evernden model, MMI contours were calculated on a 25 km square basis. These contours agree fairly well with the detailed isoseismal map Bollinger presented. As a consequence of these interpretations of seismic intensity, differing results of The Citadel study tend to reflect the more conservative (i.e., higher) ground shaking estimates by generally more severe damage estimates.

Estimated Lifeline Damage. Both studies evaluated direct damage to a number of common lifeline elements. This section compares the two studies' results for direct damage to hospitals, fire stations, police stations, railroads, and electric transmission substations.

- **Hospitals.** The Citadel researchers inventoried 11 facilities in the three counties, in which 14% of the entire state population lives. They estimated a 43% probable maximum loss to hospitals, and a 21% average expected loss. The current study inventoried 91 health care facilities in South Carolina, and estimated 27 facilities would sustain light damage (damage between 1% and 10%), 6 facilities would sustain moderate damage (damage between 10% and 30%), 9 facilities would sustain heavy damage (damage between 30% and 60%) and 3 facilities would sustain major to destructive damage (damage between 60% and 100%). These figures represent an average gross dollar damage of 10%. Note that this 10% figure reflects damage to all health care facilities in South Carolina. It is to be expected that statewide average damage should be significantly less than damage within the epicentral region, which The Citadel's 21% figure reflects.

- **Airports.** The Citadel researchers inventoried 5 facilities in the three counties. They estimated functionality for operational pavements such as runways and taxiways, and for key operational vertical structures such as control towers and terminals. For runways and taxiways, The Citadel researchers estimated 30% functionality within 1 day, 60% functionality within 3 days, and full functionality within 8 days. For vertical structures, The Citadel researchers estimated 60% functionality within 2 days, and full functionality within 2-1/2 weeks. The current study inventoried 147 facilities in South Carolina, It estimated 59% functionality of South Carolina airports during the first week, 85% functionality during the second week, and full restoration during the tenth week. The present study also evaluated damage to airports as individual units, including structures and pavements, finding 49 facilities would sustain light damage, 29 facilities would sustain moderate damage, and 9 facilities would sustain major damage.

- **Fire Stations.** The Citadel researchers inventoried 55 facilities in the three counties. They estimated a 71% probable maximum loss, and a 36% expected loss. The current study estimated 275 South Carolina facilities; 50 are expected to sustain light damage (1% to 10%), 3 are expected to sustain moderate damage (10% to 30%), and 36 are expected to sustain heavy damage (30% to 60%). These figures represent an average 7% damage.

- **Police Stations.** The Citadel researchers inventoried 10 facilities in the three counties. They estimated a 69% probable maximum loss, and a 34% expected loss. The current study estimated 70 South Carolina facilities, and estimated that 10 would sustain light damage (1% to 10%), 1 would sustain moderate damage (10% to 30%), and 8 would sustain heavy damage (30% to 60%). These figures represent an average 6% damage.

- **Railroad.** The Citadel researchers inventoried 196 miles of track in the three counties. They estimated 1 mile of track would sustain 1% damage or less, 145 miles would sustain 1-to-10% damage, and 50 miles of track would sustain 10-to-30% damage. These figures would indicate an average 9% damage to railroad track in the three counties. The current study inventoried approximately 1500 miles of track in South Carolina, and estimated 550 miles of track would sustain light damage (1% to 10%), 52 miles would sustain moderate damage (10-to-30%), and 600 miles would sustain heavy damage (30-to-60%). These figures represent an average damage of 20% to South Carolina railroad track following a Charleston event. (This is a simple measure of track damage and should not be confused with residual capacity figures, which follow on network analyses (see Chapter 6)). This difference may be explained by the significant damage to railroad track outside the three counties.

- **Electric Transmission Substations.** The Citadel researchers estimated 20% of substations in the three county area would sustain light damage, 70% of substations would sustain moderate damage, and 10% of substations would sustain heavy damage. If one defines light damage as an average 5% damage, moderate damage as an average 20% damage, and heavy damage as an average 45% damage, average expected damage to transmission substations for The Citadel study would be 20%. The present study inventoried 100 substations in South Carolina, and estimated 43% sustain moderate damage (10-to-30%), 14% sustain heavy damage (30-to-60%), and 16% sustain major damage (60-to-100%). These figures represent an average 28% damage to South Carolina transmission substations following a Charleston event. The present study estimated average damage in excess of that estimated by The Citadel. An explanation can be found in that The Citadel study considered transmission and distribution substations, while the present study considered only transmission substations. Transmission substations typically sustain more damage than distribution substations; also substations outside the three counties are significantly damaged. (Note that the average damage discussed here is a simple measure of substation damage and should not be confused with residual capacity figures, which rely on network analyses (see Chapter 6).)

- **Bridges.** The Citadel researchers inventoried 3 major bridges and 216 conventional bridges in the three counties. They estimated "serious damage" to 10 bridges, "repairable damage" to 24 bridges, and "settlement damage" to 51 bridges. They defined "serious damage" as collapse of at least one span. "Repairable damage" means that the bridge could be restored within weeks, and "settlement damage" means damage to abutments. The current study inventoried 2134 bridges in South Carolina and estimated 320, 320, 128, and 20 bridges, respectively, would sustain light damage(damage between 1 and 10%), moderate damage (damage between 10 and 30%), heavy damage (damage between 30 and 60%), and major damage (damage between 60 and 100%). The current study provide an aggregate damage of about 7% for the entire state compared to about 6% given by the Citadel researchers study for the three counties. This difference may be explained by the finding that damage to bridges outside the three counties is expected to be significant.

Conclusion. The present study estimated damage between 1/2 and 1/5th of that estimated by The Citadel study in every classification except transmission substations, railroads, and bridges. These ratios seem reasonable. The Citadel researchers examined damage in a three-county epicentral region alone; while the present study considered South Carolina as a whole. One would expect average damage over the entire state to be substantially lower than average damage in the epicentral region. The exception, transmission substations, railroads, and bridges, were discussed above.